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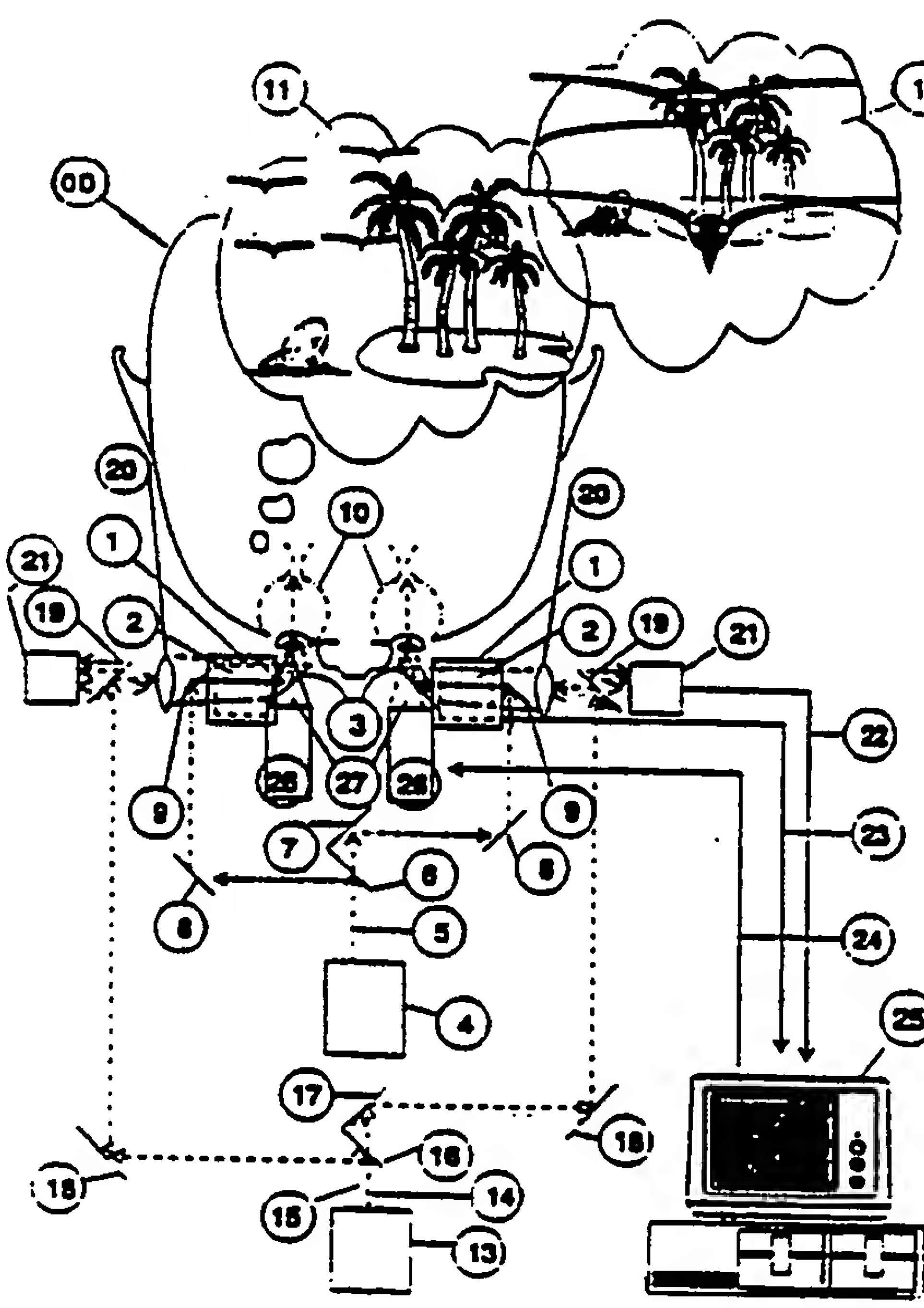
(57) Abstract

Automated binocular vision measurement and correction measure the refractions of each eye, the topography of the cornea, and the holographic corneal depth. The computer (407) assesses the visual characteristics and performs optical optimization calculations to determine the optimal corneal shapes that would provide the person with precise vision capabilities. An optimal closed pattern trace of low power level laser energy induces the malaxation of the corneal tissue. Laser energy is delivered to a stromal target (806) in the cornea (805) between the epithelium and endothelium. Predetermined parameters are measured using a moire technique. Data representive of an input fringe pattern which includes signal information of the fringe and noise is filtered in a Fourier transform technique to remove noise and back-ground. In conjunction, pattern normalization is used quantifying data from the pattern.



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VISION MEASUREMENT AND CORRECTION

by

Larry S. Horwitz

BACKGROUND

Improving eyesight is vitally important. Precise measurement and correction of physical characteristics of surfaces including features of the eye is thus also vitally important.

Since the Chou Dynasty (circa 479-381 B.C.) man has tried to correct his vision. The measurement of how much correction is required has been a major problem since that time. Typically, in contemporary practice Snellen's charts are used with a phoropter to pragmatically quantify the vision correction. This relies on patient response to quantify the measurement. Auto refractors have been invented that use the knife edge test to quantify the visual acuity via light reflected from the retina. Optical characteristics of the eye are qualified by specific aberrations. Currently, only the first three aberrations of over four hundred are used to correct vision, since this is all that can be measured.

Currently, patient refraction measurements require verbal feedback from the patient in order to quantify the refraction measurement. Thus, in order to perform the measurement on both eyes simultaneously, the number of independent variables in the concurrent indicators allow too many degrees of freedom that there would be no accuracy in the refraction of either eye. Thus, only one eye can be measured at a time.

A characteristic of the eye is needed in order to track its motion. Methods have been used that scar the cornea and track the scar. Tracking the inside edge of the iris is another technique that has been used, however, the iris diameter changes with ambient light and ocular field of regard. Thus, the error induced as the result of iris tracking is larger then the magnitude of the motion measured leaving it an invalid technique.

This invention relates to measuring the and correcting characteristics or parameters of animate and inanimate elements. In particular, the invention is directed to the measurement of surfaces including interfaces of features such as the retinal surface of the eye, the corneal topography and the depth of the cornea. Moreover the invention is directed to measuring both animate and inanimate features whether in a stationary state or in motion.

Different techniques have been developed for the accurate measurement of surface characteristics. Often these techniques rely on a laser beam which impinges on a surface and which is then reflected. A relationship between the impinging beam and the reflecting beam gives information about the surface characteristics. Where the surface characteristics are other than planar, the determination of parameters about the surface can be more difficult to obtain and analyze. Moreover, where the system relies on a physical interferometric technique, characteristics such as the mechanical stability of the system is critical in order to insure accurate measurement. Another feature of importance is the path length to a subject surface to be measured and a path length to a control or reference. Temporal and

spacial coherence are also difficult to stabilize with conventional physical interferometric techniques.

A different manner from applying interferometry to measure surface characteristics is that which is obtained from a moire' pattern. The invention is particularly related to moire' patterns.

No means exists for accurately determining surface characteristics such as those of the corneal surfaces, e.g., epithelial, Descemet's Membrane and endothelial. Thereby providing keratometric and pachymetric quantified measurements. Moreover, the Applicant is unaware of techniques whereby reflections can be obtained from different surfaces and made to be cooperative such that more specific measurements such as refraction and thickness characteristics of features of the eye can be determined. More specifically, the Applicant is unaware of any known ability to measure and analyze the data from the moire' pattern that are obtained in a manner to apply this data usefully to the object. Such usefulness would include the inherent physical dimensions of a surface, its spacing from another surface, or the degree of movement of the surface or element.

Processing fringe interferometric patterns such as moire' patterns to provide measurement characteristics of a surface is valuable. The invention also relates to the processing of fringe patterns generally and specifically, moire' patterns. More specifically, the invention is directed to the processing of fringe patterns containing information concerning characteristics related to the retinal surface, epithelial surface and endothelial surface of the cornea. With such information, valuable

refractive and diffractive characteristics of the eye can be measured.

Fringe patterns are caused by an interferometric process. In one form of such process, a collimated light beam is divided so that part of the beam is directed towards a reference and another towards a target. Reflections from the reference and target interfere to provide an interferometric pattern. Interpretation of the pattern can provide measurement characteristics about the target.

Another form of interferometric pattern is generated, a moire' interferometric fringe pattern, is by the interference formed when two grating-like transparencies, each with similar but non-identical regular patterns, overlap. The transmission of light through each grating-like transparency creates images. The moire' pattern is the image that is generated through the modulation of the two separated grating transparency images. The measurement of this pattern can provide useful information about measurement characteristics of a surface. This is related to the generation of the light, where that light is generated as a reflection from a surface. The surface can be in the eye, and the pattern is then revealing of eye measurement characteristics.

The fringe pattern can be distorted by noise in the system generating the pattern. The noise can be electronically generated, caused by the camera and optical system used in the measurement, or be background or spurious light interference. Additionally, different reflectivity characteristics of the surface unassociated with the measurement being sought can also impact accurate measurement. The reflectivity problems could

arise, for instance, where different contrast characteristics of the surface exist. Alternatively, this can be caused by different background sources directed on the surface in a manner unrelated to light associated with the optical measuring system.

The Applicant seeks to provide an improved technique and apparatus for analyzing fringe patterns.

This invention also relates to ophthalmic treatment of the cornea so as to improve the overall refractive characteristics of the eye.

Different techniques are known for treating the cornea and thereby improving eyesight. In particular, one technique is known as radial keratotomy. This technique is based on radial incisions into the corneal epithelial surface. This changes the shape of the cornea and thereby improves the refractive characteristics of the eye. Radial incisions around the pupil are effected by a laser beam so as to improve the overall refractive characteristics of the eye. Other techniques include orthokeratology which involves the remolding of the cornea by placing a contact lens on the cornea so as to shape the cornea to a prescribed curvature. Other approaches have attempted thermal treatment with radiofrequency coils through a saline bath and the use of a heated wire to perform the shaping.

A disadvantage in radial incisions around the pupil is weakening the cornea. With time the cornea loses its reshaped configuration. Applying heat in a rather broad manner without the ability to direct the energy definitively to a target can cause undesirable heat related consequences to other optical features of

the eye. Additionally, excess energy applied to the cornea can damage the eye through dryness or burning.

There is a need to provide a measurement apparatus, system and method for accurately providing parameters of selected surfaces such as discrete elements of the eye. Similarly, there is a need to provide such information for non-anatomical or inanimate elements such that parameters of the surfaces or elements can be determined more accurately and their position or movement in space measured and monitored.

Also, there is a need to provide a system for precisely treating the cornea to effect shaping of the cornea in a manner to overcome the disadvantages of the prior art.

SUMMARY

This invention provides a system, apparatus, and method for improved measurement of predetermined parameters of an element. The element may be animate such as an eye or an inanimate surface of an element such as a planar or curvilinear surface or an interface of the element or its surface with its surroundings. The invention also provides a system for cornea treatment.

According to the invention the measurement of a predetermined parameter of an element comprises the generation of a collimated light beam and the direction of that beam onto the element. The beam is reflected from the element and is directed through a first grating to develop a synthetic wave front. The synthetic wave-front is directed through a second grating to develop a moire' pattern. Analyzing the moire' pattern provides measurement data of the element.

In a preferred form of the invention, the element is an anatomical surface, preferably a surface or an interface in the eye. Selectively, this is the retinal surface and the analysis provides refractive data about the eye. Where the surface is the epithelial surface the analysis provides topographical data of the cornea. Where it is the endothelial surface, data on this provides, together with the epithelial data, a thickness measurement of the cornea.

In a preferred form of the invention, the data is obtained globally over the corneal surface, corneal thickness and the retinal surface.

In one preferred form of the invention the data is analyzed to determine movement of anatomical features such as the cornea.

In other preferred forms of the invention, collimated beams at selected wavelengths are directed to different surfaces and respective moire' patterns are obtained and analyzed. Preferably, the data for each surface is collectively analyzed. This gives information and overall parameters of the surface and the element defined by the surface.

Also according to the invention, there is provided means for receiving data representative of an input fringe pattern, where the fringe pattern is representative of measurement characteristics. The data includes signal information of the fringe pattern and noise. Filtering means is provided for removing noise so as to provide a signal information representative of the fringe pattern. Thereafter, selectively, the signal information can be scaled to remove further information representative of differences in contrast about the input fringe pattern. This provides scaled signal information representative of a fringe pattern. Demodulation of either the pre-scaled or scaled signal is affected to obtain measurement characteristics represented by the fringe pattern.

In a preferred form of the invention, the measurement characteristic is the retinal surface characteristics of the eye and the topography of the epithelial surface and endothelial surface of the cornea. With this information, refractive and diffractive characteristics of the eye are obtained. This can permit for correction by prosthetic devices such as eyeglasses or contact

lenses or by treatment of the eye with laser-directed power.

In a further preferred form of the invention, the fringe pattern is caused by a moire pattern. The filtering means is preferably a Fourier transform. The filter effectively scans the input to determine the central frequency and estimates the spectral content of the signal. The input power across the spectrum is then estimated. After the estimations are obtained, this is treated by a filter transfer function computation. Complex multiplying the transform of the input fringe signal with the transfer function, and then inverse transforming the multiplied output provides an output fringe image without noise.

In yet a further preferred form of the invention scaling of the signal is affected to eliminate the effects of different reflectivity about the surface.

Also by this invention, treatment of the cornea is achieved to effect corneal reshaping in a manner to improve the refractive characteristics of the eye. Laser energy is delivered to a target in the cornea to effect heat treatment of the cornea. There is means for generating the energy in a laser beam and for focusing this energy to a selected part in the cornea at a prescribed depth between the epithelial and endothelial surfaces. The energy is adapted to heat a target area and the laser beam traces a selected target path in the cornea. Heating the corneal matter along the path thereby changes the shape of the cornea.

In a preferred form of the invention, the traced path is a closed loop in the form of a Schwalbe's-

like line. The effective " Schwalbe's line" may be a regular curve or an irregular shape.

Preferably, the heated area is the stromal region in the cornea, and the laser energy is obtained from a carbon dioxide laser focused to avoid heating of the epithelial and endothelial surfaces.

In a preferred form of the invention, the laser is inter-operative with means for measuring the refractive characteristics of the eye, the corneal shape and corneal depth. As the thermal treatment is imparted to the cornea, a feedback is achieved such that the optimal refractive conditions are obtained.

In some cases, both eyes can be treated substantially simultaneously while a patient views a 3-D image through a stereoscope.

The moire technique used in this invention allows for adjustable sensitivity of measurement and insensitivity to motion of the eye to allow high quality, quantified ocular aberrations to be measured without patient response. Near infrared energy of the Nd:YAG laser of wavelength, 1.06 micrometers, has a high reflection coefficient in the choriocapillaris and pigmented epithelium of the retina. If the laser beam is well collimated when it enters the eye, the reflected wave front can be analyzed to measure many, and up to about two hundred fifty six aberrations of the eye.

Other features of the invention are now further described with reference to the accompanying drawings and detailed description.

DRAWINGS

In the appended drawings like numbers denote like parts.

FIG. 1 shows the system in accordance with the present invention for closed loop automated low energy refractive tissue-therapy for the binocular refractive correction in animals including humans, as depicted here, spectral biometers for the initial measurement of ocular optical characteristics as well as real-time feed back during the automated procedure are present for both eyes as well as the laser sources;

FIG. 2 the invention takes advantage of the spectral reflectance characteristics of the ocular surfaces in the spectral-biometers;

FIG. 3 shows the light path in a spectral-refractor;

FIG. 4 indicates the moire technique for sensing of the wave front reflected from the respective ocular surfaces of interest in the invention;

FIG. 5 shows the keratopographer beam interface with the anterior epithelial surface of the cornea;

FIG. 6 illustrates the light path of the keratopographer beam as it samples the entire epithelial surface of the cornea in a continuum;

FIG. 7 indicates the reflective interaction of the light used in the pachytopographer to measure the entire surface of the Descemet's membrane or endothelium,

this surface is related to the epithelial surface to provide the pachymetry;

FIG. 8 shows the optical path of the pachytopographer laser beam;

FIG. 9 is the flow of the algorithm that processes each of the moire patterns as they occur from the light reflections from each of the ocular surfaces of interest in this invention and the ocular characteristics that they provide;

FIG. 10 shows the noise and background filtering technique as used in FIG. 9;

FIG. 11 shows the technique by which the moire patterns are processed in order to normalize the contrast over each entire pattern, this is the final step in processing the pattern before the wave front data is extracted from them;

FIG. 12 indicates the "trackability" of the moire pattern from the eye (these patterns have not been processed as described in FIGURE's 10 and 11) providing an ideal eye tracking system;

FIG. 13 illustrates the low energy delivery optics to the later half of the stroma, this is an f/0.76 beam incident onto the cornea;

FIG. 14 is the power budget when a carbon dioxide laser beam is used in the corneal tissue therapy for refractive correction, this delivery system is not restricted to this laser;

FIG. 15 are the trace patterns for typical vision aberration, i.e. myopia, hyperopia and astigmatism; and

FIG. 16 is the closed loop algorithm for the automatic vision correction system with automatic feed back.

DESCRIPTION

Introduction and Overview

There is provided a system for automatic closed loop binocular vision correction.

The refractions of both eyes of the patient are measured simultaneously as a three dimensional perception video is viewed. The predominant action changes from the near field of view to the far field in a contiguous manner in combination with dark to bright fields. Concurrently, the shape and thickness of the cornea are measured continuously throughout the entire extent of the cornea. These measurements are made at the frame rate of the video camera in the system, e.g., 60 measurements per second. Anomalies are disregarded. The field distances and dark shades are temporally correlated with the depth of field (i.e., near sighted or far sighted) under going investigation.

After a period of measurement (less than a minute) the data is manipulated and the complete optical characteristics of both eyes are known. The optical aberrations of the eyes are quantified in Zernike polynomials measuring 256 aberrations simultaneously (as opposed to the 3 aberrations measured in contemporary refractions). Since the polynomials are orthogonal, the aberrations are separable and can be treated as such. An optimization optical analysis is performed that treats the cornea as the deformable element. Simultaneous far field and near field optimization are performed in order to optimize the optical capability in both fields and all intermediate points. Constraints are put on the corneal manipulation in both magnitude and direction of local

displacement and spatial frequency content of the variation. The cornea are then modeled in finite element representations for both structural analysis and heat transport analysis as reported by J. A. Scott in "A finite element model of heat transport in the human eye", Phys. Med. Biol., Vol. 33, No. 2, 227-241 (1988).

These models are then used to determine where to heat the stromal region in order to generate the corneal shape determined. The constrains put on this analysis are that the thermal energy must be applied to the later half of the corneal depth, the trace pattern is to be a closed loop and the temperature rise in the cornea is not to be more than 10° C. The closest fit to the corneal shapes is determined. If the precise shapes are not achievable, optical analyses are performed on the best fit corneal shapes to determine if the figure of merit is within our specifications. If satisfied we go to the next step; if not the two analyses are optimized. This optimization is performed by eliminating the highest order aberrations from the correction. Thus, potentially only 60 aberrations will be corrected. Trace patterns and dwell times along the pattern are now defined for each eye.

Laser gimballing systems directs the laser energy along the prescribed patterns. Through all of this time (roughly, 10 seconds) the eye motion sensor keeps track of the eye motions. If the eyes move, the biometers can still provide the measurements. If the eyes move during the laser tracing procedure, the data is fed into the gimballing system to provide the compensation. In the case of a radical movement the therapeutic laser system would turn off; then resume again as soon as the tracking of the eyes is re-initiated. As the corneal

malaxation is induced if the expected bending does not occur, new control laws are developed at each location so that in real time the dwell time of the laser energy is adjusted. As the thermal trace is completed the refractions of the eyes are again measured. If within the limits allowed, the procedure is recorded and stored in the patient file. If on the other hand the refraction measurement falls outside the required limits, the procedure is re-initiated. If after several iterations the limits cannot be met the system indicates the maximum correction achieved and records the results in the patients files.

The biometers measure the optical wave fronts reflected from the two corneal surfaces and the retina. Spectral reflectance characteristics of these surfaces allow the segregation of the wave fronts so that all optical characterizations can be measured simultaneously. The spectral reflection peaks are as follows:

Corneal epithelial surface	470 nanometers
Corneal endothelial surface	525 nanometers
Retinal surface	1060 nanometers.

The 1060 nanometer beam is collimated and directed into the eye. It is focused by the corneal media and the lens, reflected from the retina and then exits the eye by the same path. Wave front analysis is performed by passing the light through two Ronchi gratings that are arranged parallel in planes normal to the direction of propagation and rotated with respect to each other in those planes. The resulting moire pattern is imaged on a mat screen and then recorded by a video camera. The recorded image is processed via Fourier transform techniques and the image contrast is normalized

throughout the pattern. Closed form equations are then applied point by point (i.e., pixel by pixel) to derive the shape of the wave front. With the spatial characteristics known, the wave front is then fit to 256 orthogonal Zernike polynomials. Each of the coefficients of the polynomials is then reduced by a factor of one half to compensate for the double pass characteristic of the measurement. Now the optical aberrations of the eye are defined precisely.

An argon ion 470 nanometer laser beam (or any other laser emitting in the 470 nm spectral region) is collimated then passed through an f/1.25 converging lens and directed toward the center of curvature of the cornea. This light is partially reflected form the surface of the cornea. The reflected light is collected by the f/1.25 lens and directed toward the same Ronchi gratings. The resulting moire pattern is spectrally separated from the refractor pattern and processed in the same manner. Since the reflection is from a single surface the double pass effect does not occur and the polynomial coefficients are not divided by 2. This data is the precise topographical description of the corneal surface. This is the keratopographer system.

Since the moire pattern moves with the eye and the pattern uniquely defines the surface of the eye, the pattern can be tracked to qualify and quantify the motion of the eye. Simple eye motion can be characterized by tracking the transverse plane and area tracking in the axial direction. Detailed eye motion tracking is achieved by this technique integrated with the actual analysis of the moire pattern. This eye dynamics sensor is used to track the motions of the eyes during this entire procedure. The subsystem of the invention can be

used in Heads-Up-Display (HUD) system for fine pointing and tracking mechanisms; mental alertness indicator that is characterized by eye motion (sporadic or intentioned) used to detect falling asleep, drug usage or alcohol usage; video games where eye motion is an interaction with the game; and in research where eye motion is a parameter.

The final biometer is the pachytopographer that measures the corneal depth continuously throughout the corneal region. The same argon ion laser (or any other laser producing light in the 525 nanometer spectral region) also produces a 525 nm beam. By directing the beam through the same optical (f/1.25) path, as the keratopographer, a portion of the light is reflected from the endothelial surface or Descemet's membrane of the cornea and is provided the same wave front sensing after spectral separation from the other two beams. This data is the topography of the endothelial surface. By correlating the endothelial and epithelial topography and subtracting the pachymetry of the cornea is provided.

The low energy refractive tissue-therapy system makes use of the thermal effects of light. Photometric power itself does not cause therapeutic heat. Power density causes the heating that induces the malaxation of the corneal stroma tissue, the lamella. The power densities at the anterior epithelium and in the later half of the stroma can be chosen by appropriately selecting the convergence rate, or f-number, of the beam, the power in the beam and the wavelength of the beam that lies within any spectral absorption band of the water around the stromal lamella.

In this invention, the predominant absorption band of water (H_2O) is used. The intent is to heat the lamella via convection rather than the application of photometric energy directly to the tissue (energy applied to human tissue may have negative long term effects, e.g., cancer or mutated tissue). However, this optical configuration can be applied to any optical delivery system used in thermokeratoplasty (TKP) or photo-thermokeratoplasty. There are other absorption lines 2.6 micrometers, 3.9 micrometers and 6.05 micrometers according to M. A. Mainster in "Ophthalmic applications of infrared lasers-thermal considerations", Invest. Ophthalmol. Visual Sci., Vol 18, No. 4, 414-420, (1979). Lasers operating in these regions are also useful for this application. There are two absorption bands, at 1.3 and 3.4 micrometers, which are strictly for the lamella. Though use of this wavelength is not recommended in this invention applications of lasers of these wavelengths will also make use of the optical delivery system in this invention for the most effective TKP application.

The therapy beam is pointed to the later half of the stroma with a f/0.76 beam. The pachytopographer and keratopographer data are used to correctly position the beam to the 0.25 millimeter accuracy. Using a carbon dioxide laser the power incident on the eye is 0.2 watts with an intensity of less than 5 milliwatts per square centimeter, which when partially absorbed in the stroma causes no malaxation of the lamella. The focus of the beam, and the region where the intensity is high enough to induce the lamella malaxation, is a spherical volume 25 microns in diameter. Less than a microwatt arrives at the Descemet's membrane and endothelial surface of the cornea. The laser is gimballed by x,y,z linear motor

drives under the control of the computer algorithm that derived the trace and using the data from the biometers.

Detailed Description

FIG. 1 schematically shows an embodiment of the invention. This figure can be split into two monocular systems thereby proceeding with one eye at a time. The subject 00 looks into the system and view two displays 1 simultaneously, i.e., one with each eye 10. The displays are viewed via the reflections from the two beam splitters 3 and 2. A three-dimensional dynamically moving scene is provided the subject since each of the displays is playing a video of separate cameras having the perspective if each eye. An example of this is illustrated in 11 and 12 with the birds flying from far away toward the subject. The subject is told to watch the moving objects in the scene thus he is adjusting his focusing field over a wide range. As the depth of field is changing, the target brightness and contrast is changing. All of these parameters are temporarily correlated to the biometers to accurately calibrate the refraction measurements being made.

In FIG.2 the spectral reflectance characteristics of the eye 101 are illustrated. Assume a wide spectral band white light source 102 illuminating the eye. A predominant spectral region of the light will be reflected from each surface of the eye. The cornea 103 has two surfaces of interest and the retina 108 provides the reflection for the optical system sampling wave front. Though there is specular reflection at each surface there is a spectral response embedded in each reflection. Thus, at each surface there is a different "color" reflected. Spectral reflection 104 from the

anterior epithelial corneal surface is nominally 470 nanometers. Descemet's membrane and the endothelial are at the back surface of the cornea. Peak spectral specular reflectance 105 occurs at 525 nanometers. The lens 106 has two surfaces which can reflect energy 107 in the yellow spectral region. Finally, the retina 108 reflects 109 very strongly in the 1060 nanometer region.

The Neodymium:YAG, diode or other laser producing energy in the 1060 nm spectrum and collimator 4 in FIG. 1 provides the collimated beam 5 (dash-dot line) that is equally divided into two paths toward each eye at the beam splitter 6 then directed into the right and left eyes via fold mirrors 7 and 8, beam splitter 9 and beam combiner 3. The collimated beams pass through the optics of the eyes (or, single eye in the case of a monocular system), reflect from the retina and pass back through the eye optics and is directed back to the moire wave front analyzer 21.

This optical path is shown in FIG. 3. The collimated beam 301 reflects from the aperture sharing element 302 and is directed into the eye passing through the cornea 303, the lens 304 and on to the retina 306. It then is reflected out of the eye and this time passes through the aperture sharing element 302 on its way 307 to the wave front sensor.

The wave front sensor is schematically illustrated in FIG. 4. The wave front to be measured 401 enters the sensor and passes through two gratings 402 and 403. The gratings are in parallel planes that are rotated an angle O with respect to each other and axially displace a distance d. The resulting moire pattern 404 is visible on the matte screen 405 and imaged by the

camera 406. If the incoming wave front is as referenced and unperturbed A (dotted line) will result in a moire pattern as illustrated by pattern A. When there is aberration in the wave front as in B (solid line), an example of the moire pattern is given in B. The computer 407 then analyzes the wave front.

In FIG. 1, the path of the 1060 nm beam to the computer image via 22 then the analyzed beam provides the objective refraction measurement of the eyes, 25. The analyzed wave front is temporally coordinated with the focus require by the video programming, as indicated by 23, to assess the entire field and contrast acuity and accommodation.

In order to provide keratopographical measurements of the cornea of eye 10 a coherent light source producing radiation in the 470 nanometer region is required. In FIG. 1 13 is that radiation source. Light beam 14 (dashed line), the collimated coherent beam from 13, is divided into two beams at beam splitter 16 and directed toward each eye via fold mirrors 17 (left eye only), 18, beam splitters 19, through the nulling lenses 20 and beam combiners 3. Light reflected from corneal epithelial surfaces is directed back through nulling lens 20, through beam splitters 19 into the moire' wave front analyzer.

In FIG. 5 the collimated beam 501 (14, FIG. 1) is focused by nulling lens 502 (20, FIG. 1) such that the converging light 506 is focused near the center of the radius of curvature of the cornea 503, r (505), of the eye 504. Light specularly reflect form the corneal surface will be referenced to the focus of 502 as the

reflected light 501 (left hand pointing arrows) is directed toward the wave front analyzer.

Three colors will be incident onto the wave front analyzer. In order to analyze each wave front spectral filters are used on the camera focal plane of separate from the camera, in which case three cameras will be required in 21, FIG. 1.

Keratometric measurements are made with the optical system in FIG. 6. Collimated 470 nanometer light 602 (14, FIG.1) is partially reflected from beam splitter 603 (19, FIG.1) and directed onto the eye as previously described. Reflected light partially passes through the beam splitter 603 and 606 toward the wave front analyzer.

Pachytopographical data is measured by measuring topographical data from the Descemet's membrane and/or endothelial surface. Data is correlated with the keratopographical data to obtain the pachytopographical data.

In FIG. 1 525 nanometer spectral band light 15 (dotted line) is obtained from 13. An Argon Ion laser can be used as the source of both 14 and 15. Light 15 is divided toward each eye via the same optical path as 14. Upon reflection from the endothelial surface and/or Descemet's membrane 15 traces the same optical path (except for wave front variations due to the respective reflection surfaces) to the wave front analyzer.

In FIG. 7 the path of the 525 nm band light, pachytopographer beam, indicates the input beam 701 (15, FIG. 1) is focused by the nulling lens 702 (20, FIG. 1) toward the center of curvature of the cornea 705 (505,

FIG. 5). Light 701 passes through epithelial surface 703 specularly reflects from the endothelial surface and/or Descemet's membrane 707. Reflected wave front 701 (left hand going arrows) are referenced to the focused wave front of 702.

Optical system of pachytopographer is schematically shown in FIG. 8. Measurement beam 801 (701, FIG. 7) is partially reflected from beam splitter 802 (19, FIG.1) toward eye, as described in FIG. 7. Specularly reflected light partially passes through 802 with the output wave front 807 directed toward the wave front analyzer.

Methodology for analyzing moire' patterns to describe the ocular parameter of interest is schematically shown in FIG. 9. After the patterns at the three different wavelengths are spectrally segregated, patterns are filtered with respect to noise and spurious background. It is necessary to normalize the pattern contrast that is a result of surface reflectance and transmission inhomogeneity. Patterns are then reduced to analytic wave fronts, Oster, et al., in "Moire' Patterns", Scientific American, May 1963, pp. 54-63. With respect to the pattern analyzed, the surface or wave front of concern is provided. Keratometry data is correlated with Descemet's membrane and/or endothelial surface data to provide the pachymetry data.

In FIG. 9, the input moire' pattern 908 is directed to block 909 which is the filter to remove noise and background. The moire' pattern 908 can be shown with fuzzy light and dark regions. After filtering in block 909, the pattern becomes discrete and separate dark and light lines as indicated in block 910. As can be seen,

the dark lines have different degrees of darkness which is caused by different surface reflectivity and/or transmission characteristics with respect to the element being measured. The signal is represented by block 910, is directed then to the means for removing information representative of differences in contrast about the fringe pattern as indicated by block 911. This effects scaling of the fringe pattern to provide a signal as indicated in block 912 which represents dark lines of equal intensity. The output signal 912 is directed to means for demodulating the scaled signal information of the fringe pattern to obtain measurement characteristics represented by the fringe pattern, such demodulating means being generally indicated by block 913. From block 913, the different characteristics of refraction, epithelial surface, and endothelial surface measurements can variously be obtained as diagrammatically illustrated through arrows 914, 915 and 916, respectively. The information can then be further processed appropriately. The refraction information can give aberration analysis. The epithelial surface information can give keratometry data, and the information about the epithelial surface and endothelial as indicated collectively by arrows 917 and 918 can be used to give pachymetry data. The representations of the demodulated signal information can be received multiple time over a short temporal period. Anomalies are eliminated and there are means to average the multiple representations to obtain an appropriate output signal 914, 915 and 916 representative of the measurement characteristics.

The methodology of filtering to eliminate noise and background from the respective pattern is shown in FIG. 10. Local areas of the pattern are chosen with respect to the spatial variation of the noise and

background. With respect to each local area a guard band is chosen encompassing it in order to transform the data to the spatial frequency domain using a Fourier transform. The fundamental frequency of the domain is that provided by the configuration of the moire' wave front analyzer. A noise and background power spectrum data is then estimated and combined with the signal estimation to provide the complex transfer function H. Spatial frequency data of the noise/background free pattern, P, is defined by the complex product of the input pattern power spectrum and the transfer function. An inverse Fourier transform of P is the output moire' local area pattern. Local area patterns are then moved throughout total pattern in order to effect the entire moire' pattern.

In FIG. 10, the input moire' local area pattern 1000 is directed into a block 1001 for effecting a Fourier transform of the input and pre-processed moire' pattern. The pattern in the spatial frequency domain is represented by $M(jw_x,jw_y)$. The output from the Fourier transform is indicated as a signal. The signal is directed to means 1002 for estimating the signal spectral content as indicated by $f_o=p/(2\sin 0)$. The output from block 1002 provides a signal as indicated by $S'(jw_x,jw_y)$.

Secondly, there are means 1003 for estimating the input power spectrum and the representation on spatial domain component is indicated by $|M'(jw_x,jw_y)|^2$. Both these estimations are directed as indicated by arrows 1004 and 1005 to a filter transfer functions block 1006 where a computation is effected to provide an outlet signal represented as:

$$H(jw_x,jw_y) = \frac{|S'(jw_x,jw_y)|^2}{|M'(jw_x,jw_y)|^2}.$$

Normalized pattern contrast is achieved via the methodology describe in FIG. 11. Spatial intensity characteristics of the pattern are determined. A window dimension is then determined. Window is then moved throughout the pattern in which a maximum and minimum intensity at each location is determined. The pixel value p(x,y) is then adjusted to the normalized value p'(x,y):

$$p'(x,y) = \frac{p(x,y) - p(min)}{p(max) - p(min)}$$

for all (x,y) within each window (block **1120**).

The noise free moire' pattern image **1111** is directed along line **1112** to a circuit **1113** to determine the centroid and variance of all the pattern p(x,y). The output data **1114** is directed to block **1115** where the local area window size is determined in order to locally adjust for contrast inhomogeneity. Window **1116** is then moved throughout the entire pattern **1117** locally determining the maximum, p(max), and minimum, p(min), pixel values (intensity) within the window **1118**. This data is then passed **1119** to the normalizing equation for every point (x,y) within the window **1120**. Output pattern is now normalized in contrast (as indicated in FIG. 9, **912**).

Effectively, the compensation means includes means for dividing the fringe pattern p(x,y) into discrete pixels and means for defining a neighborhood about each pixel and means for collecting data within that neighborhood, the neighborhood being that data within the window. There are also means for computing the minimum and maximum contrast signal as

indicated by block **1118** within the neighborhood or window and then the means is scaled to produce a scaled value of the pixel within the neighborhood as indicated in block **1120**.

This signal is suited for wave front analysis and pattern tracking.

Moire' patterns derived from the corneal epithelial surfaces provide a characteristic by which the eye can be tracked as shown in FIG. 12. In plane tracking of the centroid of the pattern provide coarse tracking of eye to within 1.41 pixels. Analysis of the patterns provides the fine tracking algorithm. Area tracking of the pattern provides axial translation with pattern analysis again providing fine tracking data.

In FIG. 12, the illustration indicates the manner in which tracking can be effected. This is illustrated relative to the axis as depicted in the x,y,z coordinate system as illustrated in the axis diagram to show three dimensional representations **1200**. The point of juncture between the x,y,z axis is the 0 indicator. The moire' pattern as indicated in the x,y plane **1210** shows the effect of the relative movement when at the intersection 0 the pattern **1201** is represented. Movement to the left is indicated pattern **1202** and movement to the right along the wire plane is indicated by pattern **1203**. Movement along the z axis **1211** into and away from the x-y plane **1210** is indicated such that movement away from the x,y plane is indicated by pattern **1204**, movement at the intersection by the 0 position, and movement from the intersection out of the paper by pattern **1205**.

Compound movement being a combination of movement in the x,y and z planes as indicated by arrow 1212 causes a representation 1207. Further movement is indicated by arrow 1213 which gives you a representation 1206. Movement as indicated by arrow 1214 gives you a representation 1208 and further movement is indicated by arrow 1215 which gives you a representation 1209.

In application to the refractive tissue therapy system, the location is fed back to the computation system on 22 FIG. 1 and the laser gimballing 24 FIG. 1.

A mechanism of delivery of low energy refractive tissue therapy is shown in FIG. 13 (26 FIG. 1). The input beam 1301 (27 FIG.1) is focused by a f/0.76 (or similar) lens 1302 to the later half of the corneal 1305 stromal region 1306 to a spot 1307 20 to 50 micrometers in diameter (assume a spherical volume). Therapy be is focused such as to not deliver the energy density to the corneal epithelial surface 1303 or the endothelial surface 1309 that will induce enough thermal energy to cause malaxation of the tissue. Malaxation is only induced in volume 1307. Gimballing (x,y,z) of the therapy beam is performed for local treatment throughout the entire cornea, as discussed later. In the case of a carbon dioxide (CO_2) laser the power budget of the therapy beam is shown in FIG. 14. Though 0.2 watts is incident upon the eye, power density is low enough that malaxation will not occur. At the focus around the 20 to 50 micrometer diameter volume the power density is high enough to induce the 10° C elevation of temperature. At the endothelial surface the intensity will not cause endothelial cell damage.

Typical and representative trace patterns of the therapy beam is illustrated in FIG. 15. It is evident that the patterns form a pseudo Schwalbe's line. Schwalbe's line holds the cornea erect in the spherical form. By forming a closed loop trace pattern **1502 a,b & c** the corneal malaxation has shown to provide a steady state form of the cornea post-malaxation. As representative, trace **1502a** will provide a correction of myopic sight impairment. Likewise **1502b** hyperopic correction and **1502c** is a correction for this arbitrary astigmatism.

The invention performs the high order corrections utilizing a thermal corneal tissue therapy technique in conjunction with optical and corneal structural analysis.

In FIG. 16, the automated system is illustrated in a closed loop. With incoming data providing the refraction impairment, keratometry and pachymetry from the biometers (**1601**, **1602** and **1606**, i.e., **22** and **23** in FIG. 1), optimization for the corrected ocular optical system is determined by least squares fitting the measurements (who are themselves locally discriminated and averaged) to a discrete number of Zernike polynomials in the optical optimization processor **1615** (in computer **25** FIG. 1). Desired corneal shape is derived (given spatial constraints), or contact lenses of spectacles are defined (**1618**). In the case of corneal therapy, a finite element model of the cornea is developed form the keratometry and pachymetry data in block **1616**. Thermal therapy is then defined by the thermal analysis in block **1617** as to locations of the therapy, i.e., laser beam trace, and dwell times of the beam at each site (**1621** and **24** in FIG. 1). For medical acceptability the data is displayed in block **1619**. Spatial coordinates of the beam are the

given 1620 to the gimballing system 1615 to trace the closed loop trace. As well, locations of the eyes are provided via the keratopographers 1602 and the tracking algorithm 1614 in real-time on line 1613 into the location file 1614 for the thermal therapy gimballing system. Upon gimballing completion the optical characteristics of the eyes are again measured 1601 and 1602. If criteria are passed for the optimal patient visual correction in block 1603, the data is passed 1604 to block 1605 where it is recorded and the procedure is complete. On the other hand if the criteria is not passed, the new data is passed back through the system, i.e., to blocks 1609 and 1608 (the current pachymetry is again measured 1606 and provided to block 1607) to initiate a new iteration of the corrective procedure. Thus, closing the vision correction control loop.

The system as indicated operates in a closed loop to effect optical measurements and also to determine the degree of corrective treatment that is necessary for the optical element. When the optical treatment is effected, the closed loop can provide different refractive signals and this can be adapted so that ultimately the optical conditions are rectified.

The invented spectral-refractor system requires no patient conscious feed-back. Thus, a binocular refraction can be performed. The corneal topography and the corneal holographic depth measurement require no patient feedback. Therefore, all of the parameters of the patient's visual characteristics can be measured simultaneously in a binocular mode.

Corneal global topography is a mechanism needed to sample (i.e., make measurements from) the entire

surface of the cornea. By combining ocular spectral reflectance information with wave front sensing technology, the corneal surface topography is precisely and continuously measured. Such measurements will provide precise biometrics in order to fit contact lenses and to analyze the cornea for refractive surgical or therapeutic procedures.

The technique used in the keratometric method permits the dynamics of the eye to be tracked, i.e., an eye tracking sensor. This can qualify eye motion or quantify it to 200 microradians (or, 0.01 degree).

This technique is useful in ophthalmic surgery, refractive surgical and therapeutic procedures, pointing and tracking in helmet mounted systems, sensors to determine if a person is falling asleep (e.g., automobile sleep alarms), mental acuity tests (e.g., alcohol and drug tests), and video games in which eye tracking would be used as the interaction with the game.

Laser energy with the appropriate spectral absorption characteristic of the stromal region in coordination with the optical delivery system produces the therapeutic effect needed to induce refractive alteration. Corneal stromal region temperature must be elevated by 10° C in order to produce the malaxation as can be derived from E. L. Shaw and A. R. Gasset in "Thermokeratoplasty (TKP) Temperature Profile", J. Invest. Ophthalmol. 13, No. 3, 181-186 (1974), and J. A. Scott in "The computation of temperature rises in the human eye induced by infrared radiation", Phys. Med. Biol., Vol. 33, No. 2, 243-257 (1988). Temperature rise is controlled by the dwell time of the focus of the laser beam. Corneal shape change is controlled by the trace pattern

of the gimballed laser beam. This is a low energy refractive tissue technique. An automated, closed loop control refractive correction system, integrates this with the spectral refractor, the keratopographer, the pachytopographer, and the eye dynamics sensor.

Software performs optical analysis of the eye, and structural and thermal analysis of the cornea. This is a closed loop, ophthalmic system. No conscious patient feedback is required for the system to perform. Thus, the system can be used for any mammals, e.g., veterinary, mentally retarded patients, patients who are too young to communicate or are otherwise unable to communicate.

The invention seeks to perform closed loop refractive correction to both eyes of the subject patient simultaneously and automatically. No subjective feedback from the patient will be required by the system. While viewing a three dimensional dynamic video scene, the patients ocular parameters will be measured, calculation performed and thermal refractive tissue therapy performed. The system is closed loop in the sense that if the procedure does not produce the desired refractive and corneal effects desired, it compensates for the errors automatically.

Automatic, binocular or monocular refractive measurements of the vision of subject patients without causing eye strain or requiring verbal response should be possible. Contact lens or spectacle lens prescriptions will likely be provided automatically as well as prescribed refractive surgical or tissue therapeutical procedures.

Precise topographies of corneal surface to be used in contact lens fitting, analysis of corneal scaring and lesions, ophthalmic research, and refractive surgical and tissue therapeutical procedures should be possible.

Holographic topographies of the corneal depth may be used in ophthalmic research, refractive surgical and tissue therapeutical procedures, and corneal diagnostic analysis.

Quality control of inanimate elements such as objects where the surface of the product is an indicator of the product quality is possible. Examples are ball bearings or golf balls where the sphericity is important, optical components where surface quality is important, injection molded elements where surface quality is important, and cut gem quality where the relative position of cut faces are important.

Many more examples and applications of the invention exist, each differing from the other in matters of detail only. The invention is to be considered limited only by the following claims.

CLAIMS:

1. Apparatus for measuring a predetermined parameter of an element comprising:

(a) means for generating a collimated light beam;

(b) means for directing the beam onto the element wherein the beam is reflected from the element;

(c) means for directing the reflected beam through a first grating to develop a wave front;

(d) means for directing the wave front through a second grating to develop a moire' pattern; and

(e) means for analyzing the moire' pattern to produce measurement data of the element.

2. Apparatus as claimed in claim 1 including a nulling converging lens between the element and the first grating, the nulling lens having related to the surface of the element to provide a beam front substantially parallel to the surface of the element.

3. Apparatus as claimed in claim 1 wherein the analyzing means includes computation means for removal of noise and for determining a substantially noise-free moire pattern thereby to provide measurement data of the element.

4. Apparatus as claimed in claim 1 including means for selecting a collimated beam of a predetermined wavelength suitable for reflection from a selected element.

5. Apparatus as claimed in claim 4 wherein the beam has a wavelength in the range of about 400 to about 1100 nanometers.

6. Apparatus as claimed in claim 5 wherein the wavelength is about 1060 nanometers and wherein the beam is directed onto a retinal surface of an eye thereby to permit measurement of refractive characteristics of the eye.

7. Apparatus as claimed in claim 4 wherein the beam is a Nd:Yag laser beam.

8. Apparatus as claimed in claim 4 wherein the beam has a wavelength in the range of about 400 to about 500 nanometers, and wherein the beam is directed onto an epithelial surface of a cornea of an eye.

9. Apparatus as claimed in claim 8 wherein the wavelength is about 470 nanometers.

10. Apparatus as claimed in claim 8 wherein the beam is an Argon Ion laser beam.

11. Apparatus as claimed in claim 4 wherein the wavelength of the beam is in the range of about 500 to about 550 nanometers and is directed to an endothelial surface of a cornea of an eye.

12. Apparatus as claimed in claim 11 wherein the wavelength is about 525 nanometers.

13. Apparatus as claimed in claim 11 wherein the beam is an Argon Ion laser beam.

14. Apparatus as claimed in claim 1 wherein different beams are selectively directed at different surfaces of selected elements and wherein a first beam is directed at an epithelial surface of a cornea and a

second beam is directed at an endothelial surface of a cornea and wherein the analysis means provides data of the epithelial surface, and data of the endothelial surface, and a measurement of the thickness of the cornea over a predetermined corneal area.

15. Apparatus as claimed in claim 14 wherein a third beam is directed at a retinal surface thereby to provide data relating to the refractive characteristics of the retinal surface, the beam being directed over a predetermined area of the retinal surface.

16. Apparatus as claimed in claim 15 wherein the means for analyzing the moire pattern selectively analyzes data from the beam directed the retinal surface, the beam directed at the epithelial surface and the beam directed at the endothelial surface, the analyzing means thereby providing informational characteristics of the refractive characteristic of an eye as determined by the reflection from the retinal surface, and the reflection characteristics of the eye as effected by the cornea over a predetermined area of the cornea.

17. Apparatus as claimed in claim 16 including means for analyzing the refractive information to provide data for changing the refractive characteristics.

18. Apparatus as claimed in claim 14 wherein the epithelial information is analyzed to provide data about the shape of the cornea.

19. Apparatus as claimed in claim 14 including means for analyzing the epithelial information and endothelial information for providing data about the corneal thickness.

20. Apparatus as claimed in claim 1 wherein the beam is directed at an element surface which is irregular.

21. Apparatus as claimed in claim 1 wherein the element includes a surface which is essentially curvilinear.

22. Apparatus as claimed in claim 1 wherein the surface is essentially circular.

23. Apparatus as claimed in claim 1 wherein the beam is directed at elements having multiple surfaces substantially simultaneously, and including multiple analyzing means for determining multiple characteristics of the elements.

24. Apparatus as claimed in claim 23 wherein the beam is directed to a second surface and wherein a reflection from the first surface and a second surface is processed by respective analyzing means, and wherein the surfaces are related such that the analyzing means can provide information from both the surfaces thereby to provide interrelated data of both surfaces.

25. Apparatus as claimed in claim 1 including means for storing data representative of the element parameters.

26. Apparatus as claimed in claim 1 wherein the analyzing means includes means for tracking relative movement of the element.

27. Apparatus as claimed in claim 26 including means to determine movement in any one of three dimensions.

28. Apparatus as claimed in claim 1 including directing a beam at a predetermined wavelength towards a lens surface of an eye, the wavelength being selected to be reflected from at least one of the interfaces of the lens with its surroundings in the eye.

29. Apparatus as claimed in claim 1 including means for continuously measuring the wavefront of the beam as projected in the pattern thereby to continuously obtain measurement parameters of the surface.

30. Apparatus as claimed in claim 1 wherein the surface is selectively animate or inanimate.

31. Apparatus for processing a fringe pattern, the pattern being representative of measurement characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) filtering means for removing the noise thereby to provide the signal information representative of the fringe pattern; and

(c) means for demodulating the signal information of the fringe pattern thereby to obtain measurement characteristics represented by the fringe pattern.

32. Apparatus for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) filtering means for removing the noise thereby to provide the signal information representative of the fringe pattern;

(c) means for receiving the signal information from the filtering means and for removing from the signal information further information representative of differences in contrast about the input fringe pattern thereby to provide a scaled fringe pattern; and

(d) means for demodulating the scaled signal information of the fringe pattern for obtaining the measurement characteristic represented by the fringe pattern.

33. Apparatus as claimed in either claim 31 or claim 32 including means for processing the demodulated signal information thereby to determine wavefront data representative of the measurement characteristics.

34. Apparatus as claimed in claim 33 wherein the measurement characteristics represent three dimensional topographic information.

35. Apparatus as claimed in claim 33 including means for receiving multiple representations of the demodulated signal information and including means for averaging the multiple representations thereby to obtain an output signal representative of measurement characteristics.

36. Apparatus as claimed in claim 35 including means for analyzing and presenting the measurement characteristics.

37. Apparatus as claimed in either claim 31 or claim 32 wherein the input fringe pattern is image data representative of an anatomical surface.

38. Apparatus as claimed in claim 32 wherein the image data is selectively representative of at least one of the retinal surface, epithelial surface or endothelial surface of the eye.

39. Apparatus as claimed in either claim 31 or claim 32 wherein the input fringe pattern is a interferometric pattern.

40. Apparatus as claimed in claim 39 wherein the input fringe pattern is a moire pattern.

41. Apparatus for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern;

(b) means for demodulating the data to obtain information representative of a measurement characteristic;

(c) means for obtaining further representations of the demodulated data and for averaging the data to obtain an effective average as an output signal representative of the measurement characteristics;

(d) means for removing anomalies falling significantly beyond the effective average; and

(e) means for analyzing the output signal and presenting the output signal as a representation of the measurement characteristics.

42. Apparatus as claimed in claim 41 wherein the input data is selectively representative of at least one of the surface characteristics of the eye, the surface being selectively the retinal surface, endothelial surface or the epithelial surface.

43. Apparatus as claimed in either claim 31 or claim 32 wherein the demodulation means effectively converts the data into a sinusoidal wave pattern, the sinusoidal wave pattern having phase modulated and frequency modulated characteristics, and wherein the phase modulated characteristics is representative of depth in a topographical sense and the frequency modulated signal is representative of the slope of a surface.

44. Apparatus as claimed in either claim 31 or claim 32 wherein the demodulation means effectively treats a fringe pattern as a continuing communication signal, the communication signal being analyzed by the demodulation means.

45. Apparatus as claimed in either claim 31 or claim 32 wherein the filtering means includes means for selectively analyzing discrete portions of the fringe pattern for determining local noise and background in the discrete portions.

46. Apparatus as claimed in claim 32 wherein the means for scaling provides a scaled fringe pattern, the sealing means selectively normalizing discrete portions of the fringe pattern.

47. Apparatus as claimed in claim 46 including means for comparing the data before scaling with the data after scaling thereby to obtain information about surface roughness being represented by the measurement characteristics.

48. Apparatus for electronically processing a fringe pattern to obtain measurement characteristics, the fringe pattern being representative of the measurement characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise; and

(b) filtering means for removing the noise thereby to provide the signal information representative of the fringe pattern, wherein the filtering means includes a Fourier transform based local area filter.

49. Apparatus as claimed in claim 48 wherein the filtering means includes a Fourier transform based local area filter.

50. Apparatus as claimed in claim 49 wherein the receiving data is directed to Fourier transform means, the output of the Fourier transform means being directed firstly to means for estimating the signal spectrum, and secondly to means for estimating the input power spectrum, and means for receiving the first and second spectrum estimations, the receiving means being computation means for a filter transfer function, the output of the computation means being directed to means for complex multiplying the function with the transformed receiving data, and means for receiving the complex multiplied signal and performing an inverse Fourier

transform thereby to provide an output signal representative of the fringe pattern with noise removed.

51. Apparatus as claimed in claim 50 wherein the means for signal spectrum estimation provides an estimate of a center frequency and an estimate of the spectral content of the signal, such estimates being an indication of the signal information without noise.

52. Apparatus as claimed in claim 50 wherein the input power spectrum estimation means provides an estimate of the signal information and noise of the entire input signal.

53. Apparatus for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

(a) means for receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) filtering means for removing the noise information thereby to provide the signal information representative of the fringe pattern; and

(c) means for scaling the signal information from the filtering means and for removing from the signal information further information representative of differences in contrast about the input fringe pattern thereby to provide scaled signal information representative of the fringe pattern, and wherein the scaling means is an adaptive surface roughness compensation means.

54. Apparatus as claimed in claim 53 wherein the compensation means includes means for dividing the fringe pattern into discreet pixels, means for defining a neighborhood about each pixel, means for collecting data

within the neighborhood, means for computing a minimum and a maximum contrast signal within the neighborhood, and means for scaling the minimum and maximum signal thereby to provide a scaled value of the pixel within the neighborhood.

55. Apparatus as claimed in claim 54 wherein the size of the neighborhood is selected to contain at least one fringe maximum and one fringe minimum signal.

56. Apparatus as claimed in claim 54 wherein the fringe pattern is represented by a moire pattern, and the maximum signal is represented by a dark line of the moire pattern and the minimum signal by a space between the dark lines in the moire pattern, and wherein scaling effectively adjusts each pixel to vary between a maximum and a minimum, the maximum and the minimum being applicable to adjacent pixels.

57. Apparatus for delivering laser energy to a target in a cornea region of an eye comprising:

(a) means for generating energy in a laser beam at a predetermined wavelength such that energy is absorbed by water;

(b) means for focusing the energy to a selected part in the cornea at a predetermined selected depth between an epithelial surface of the cornea and an endothelial surface of the cornea whereby the energy in the laser beam heats the target; and

(c) means for tracing the laser beam on a selected path and heating the cornea at selected targets on that path thereby to change the shape of the cornea.

58. Apparatus as claimed in claim 57 wherein the target is in a stroma region of the cornea.

59. Apparatus as claimed in claim 57 wherein the traced path forms a closed loop.

60. Apparatus as claimed in claim 59 wherein the closed path forms a Schwalbe's-like line.

61. Apparatus as claimed in claim 57 wherein the intensity at the target is in the range of between about 0.5 to about 2 watts/cm^2.

62. Apparatus as claimed in claim 61 wherein the intensity is in the range of about 1.1 watts/cm^2.

63. Apparatus as claimed in claim 57 wherein the beam focuses energy at the target to form a diameter of between about 10 to about 50 microns.

64. Apparatus as claimed in claim 63 wherein the focus diameter is about 25 microns.

65. Apparatus as claimed in claim 57 wherein the intensity of the beam at the epithelial surface is about 5 X 10^{-3} watts/cm^2.

66. Apparatus as claimed in claim 57 wherein the intensity at the endothelial is about 2.0 X 10^{-4} watts/cm^2.

67. Apparatus as claimed in claim 57 wherein the laser beam is generated by a CO_2 laser.

68. Apparatus as claimed in claim 57 wherein the laser beam is focused towards the target at a +' number of about 0.76.

69. Apparatus as claimed in claim 59 wherein the traced path is a regular curve.

70. Apparatus as claimed in claim 69 wherein the curve is selectively a circle or an ellipse.

71. Apparatus as claimed in claim 59 wherein the traced path is an irregular curvilinear shape.

72. Apparatus as claimed in claim 57 including means for measuring the refractive characteristics of the eye, means for feeding data representative of the refractive characteristics to the means for tracing the laser beam on the selected path, and means for causing the tracing means to follow a path to provide different refractive characteristics of the eye by changing the shape of the cornea in terms of the traced path and thereby to effect a change of the refractive characteristics.

73. Apparatus as claimed in claim 57 including means for directing a patient to view a three dimensional image through a stereoscope, means for measuring the refractive characteristics of the eyes of a patient, means for measuring the shape and thickness of the cornea of the eyes and means for determining the refractive changes necessary to change the overall refraction of the eyes, and means for delivering the laser beam to the target on a selected path to thereby change the refraction characteristics of the eyes.

74. Apparatus as claimed in claim 72 including computer control means for coordinating the measuring and changing characteristics.

75. Apparatus as claimed in claim 74 including feedback means for continually controlling the laser beam operation and tracing means.

76. Apparatus as claimed in claim 57 including directing the energy to water molecules in a stroma of the eye.

77. Apparatus as claimed in claim 57 wherein means is provided for analytically dividing the corneal region into finite elemental areas, computing means for analyzing relative stress factors between the finite elemental areas, means for determining the heating effect on one or more selected finite elemental areas relative to stress factors between the elemental areas thereby to change the physical relationship between the respective elemental areas and the physical corneal material, and means for directing the application of heat to selected elemental areas.

78. Apparatus as claimed in claim 57 including means for optically analyzing the corneal region in elemental areas, and means for applying a structural analysis technique to the elemental areas to provide information about the effect of applying heat to the elemental areas.

79. Apparatus as claimed in claim 78 including means for applying energy to selected elemental areas as determined by the finite elemental analysis thereby to change the optical refractive system in the eye.

80. Apparatus as claimed in claim 77 wherein the selected elemental areas are the target of the beam.

81. Apparatus as claimed in claim 79 wherein the selected elemental areas are the target of the beam.

82. Apparatus as claimed in claim 73 including means for changing substantially simultaneously the refractive characteristics of two eyes of a patient.

83. Apparatus as claimed in claim 73 including means for selectively viewing images at different depths at different predetermined times, means for obtaining refractive information at the respective predetermined times, means for determining data for changing the refractive characteristics, and means for delivering a laser beam to heat the cornea and thereby change the refractive characteristics according to the determined data.

84. A method for measuring a predetermined parameter of an element comprising:

(a) generating a collimated light beam;

(b) directing the beam onto the element wherein the beam is reflected from the element;

(c) directing the reflected beam through a first grating to develop a wavefront;

(d) directing the wavefront through a second grating to develop a moire pattern; and

(e) analyzing the moire pattern to produce measurement data of the element.

85. A method as claimed in claim 84 including converging the beam being related to provide a beam front substantially parallel to the surface of the element.

86. A method as claimed in claim 84 including removal of noise and determining a substantially noise-

free moire pattern thereby to provide measurement data of the element.

87. A method for processing a fringe pattern, the pattern being representative of measurement characteristics, comprising:

(a) receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) removing the noise thereby to provide the signal information representative of the fringe pattern; and

(c) demodulating the signal information of the fringe pattern thereby to obtain measurement characteristics represented by the fringe pattern.

88. A method for processing a fringe pattern, the fringe pattern being representative of measurement characteristics, comprising:

(a) receiving data representative of an input fringe pattern, the data including signal information of the fringe pattern and noise;

(b) removing the noise thereby to provide the signal information representative of the fringe pattern;

(c) receiving the signal information from the filtering means and for removing from the signal information further information representative of differences in contrast about the input fringe pattern thereby to provide a scaled fringe pattern; and

(d) demodulating the scaled signal information of the fringe pattern for obtaining the measurement characteristic represented by the fringe pattern.

89. A method for delivering laser energy to a target in a cornea region of an eye comprising:

(a) generating energy in a laser beam at a predetermined wavelength such that energy is absorbed by water;

(b) focusing the energy to a selected part in the cornea at a predetermined selected depth between an epithelial surface of the cornea and an endothelial surface of the cornea whereby the energy in the laser beam heats the target; and

(c) tracing the laser beam on a selected path and heating the cornea at selected targets on that path thereby to change the shape of the cornea.

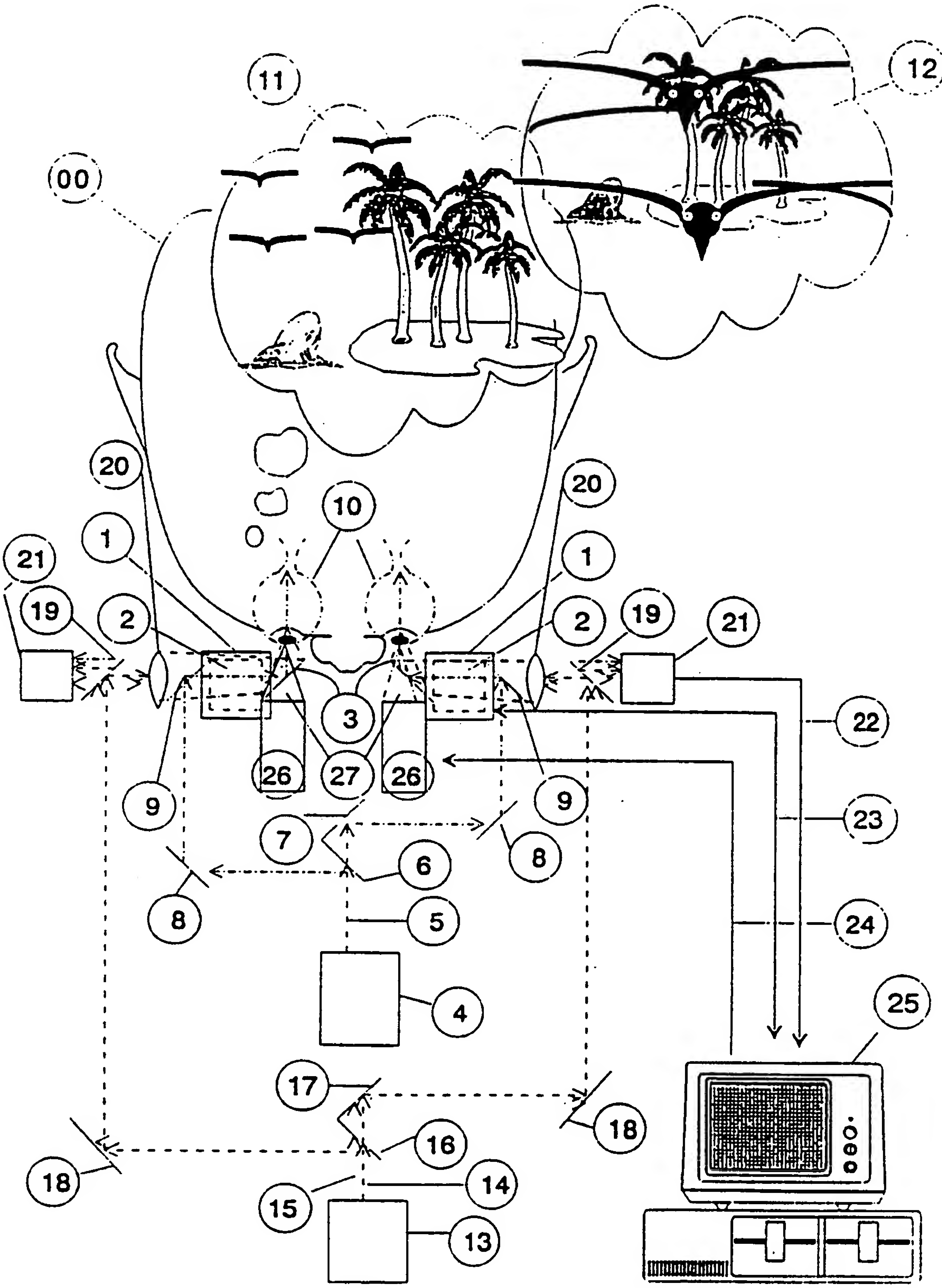
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Figure 1

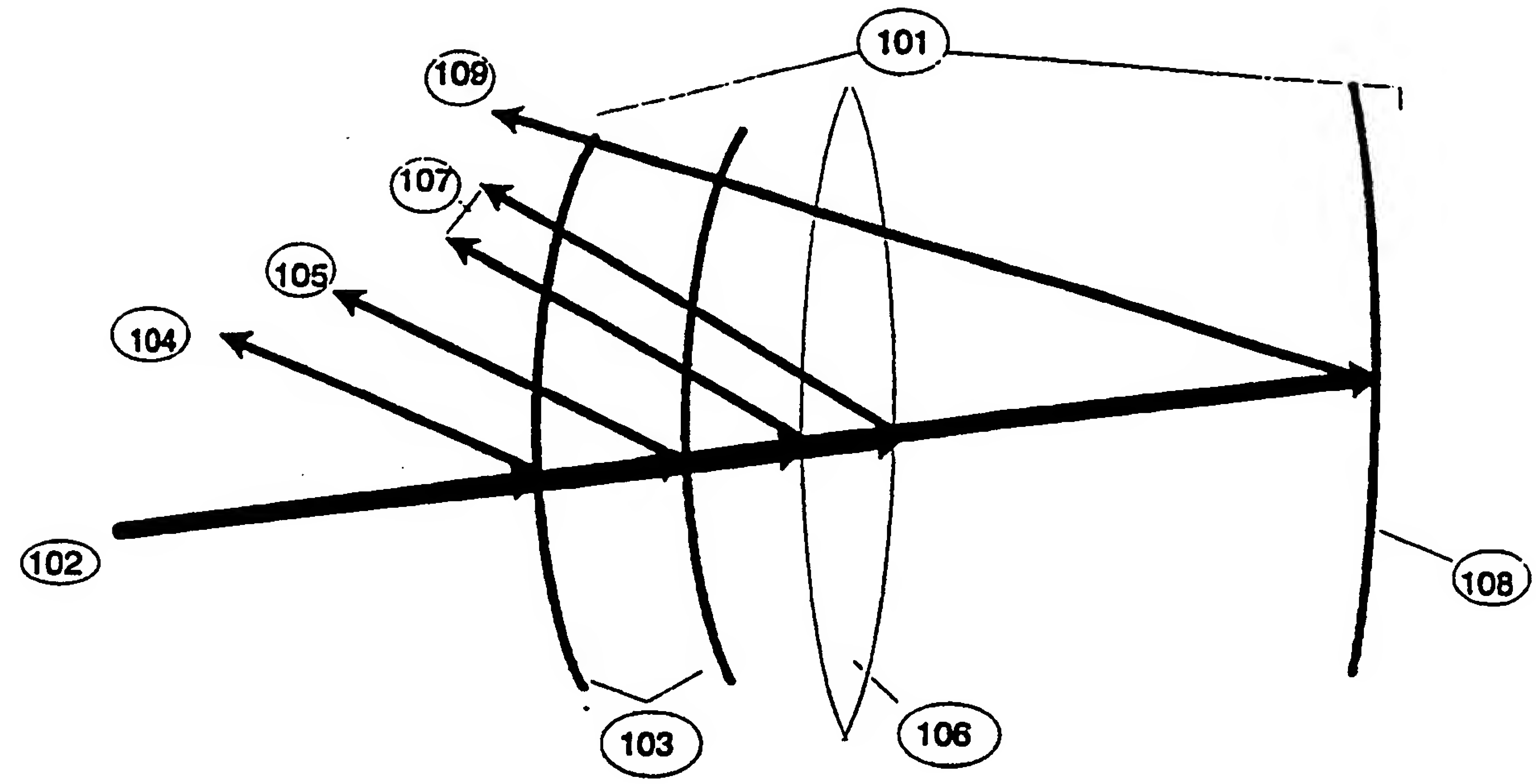


FIGURE 2

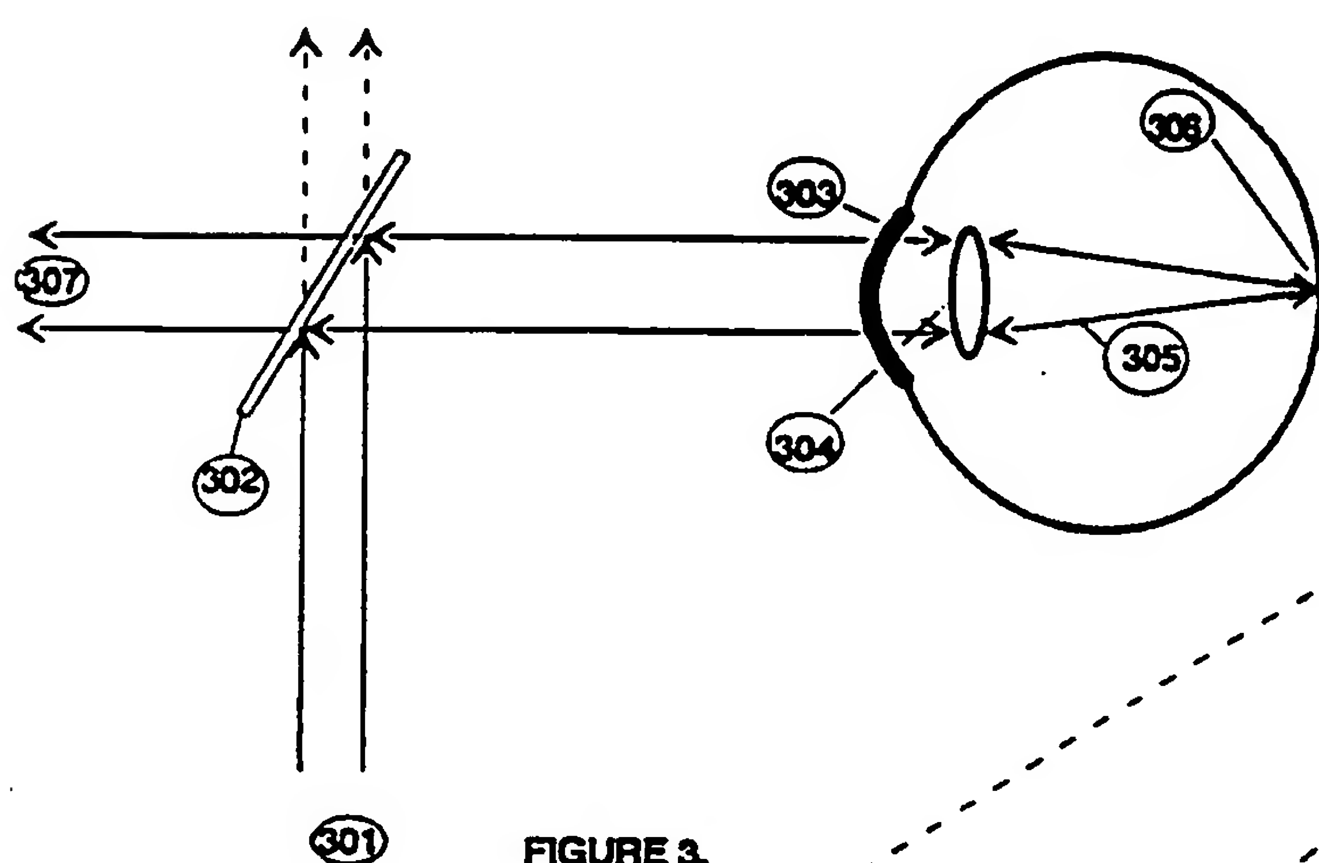


FIGURE 3.

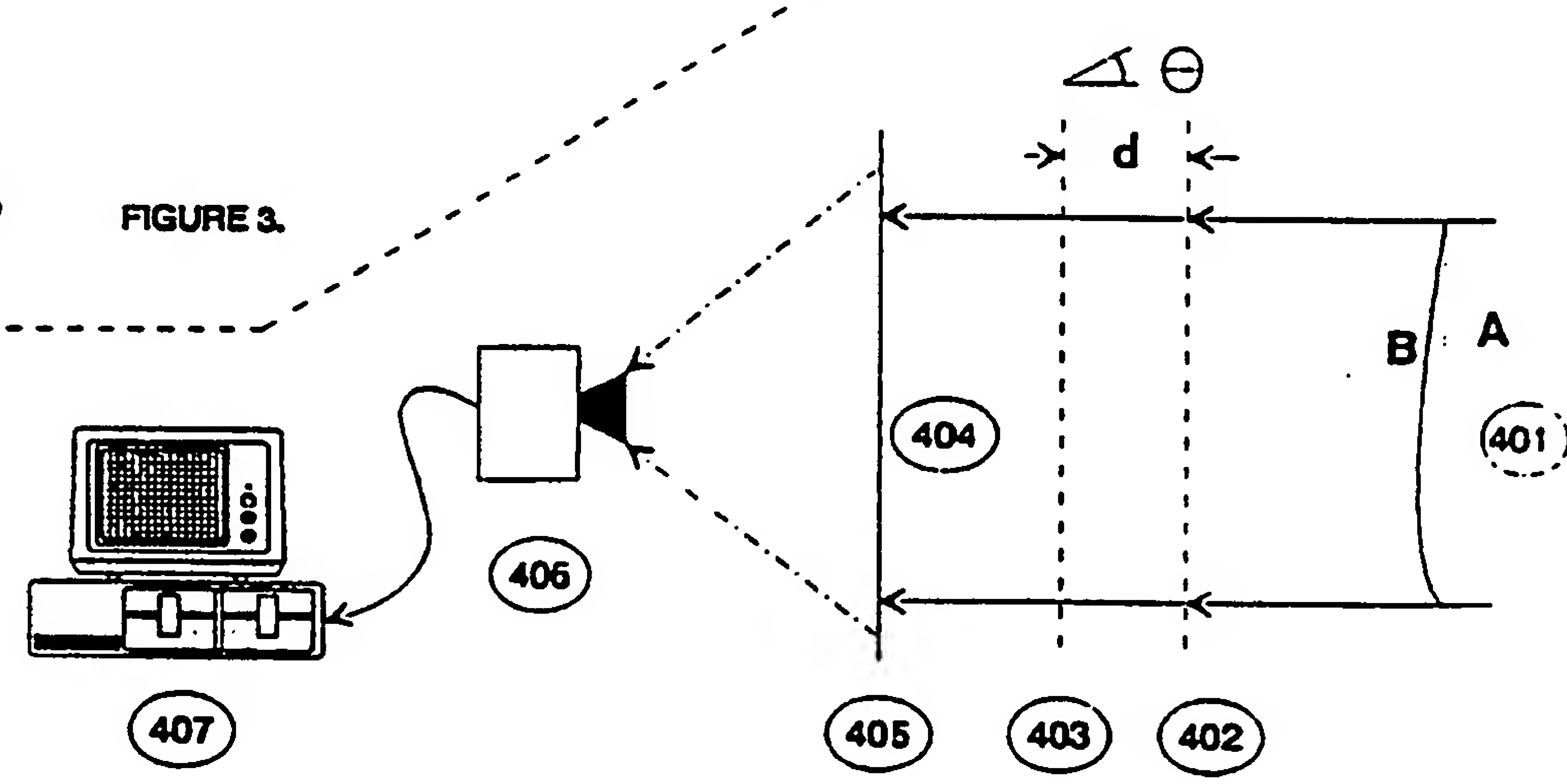


Figure 4

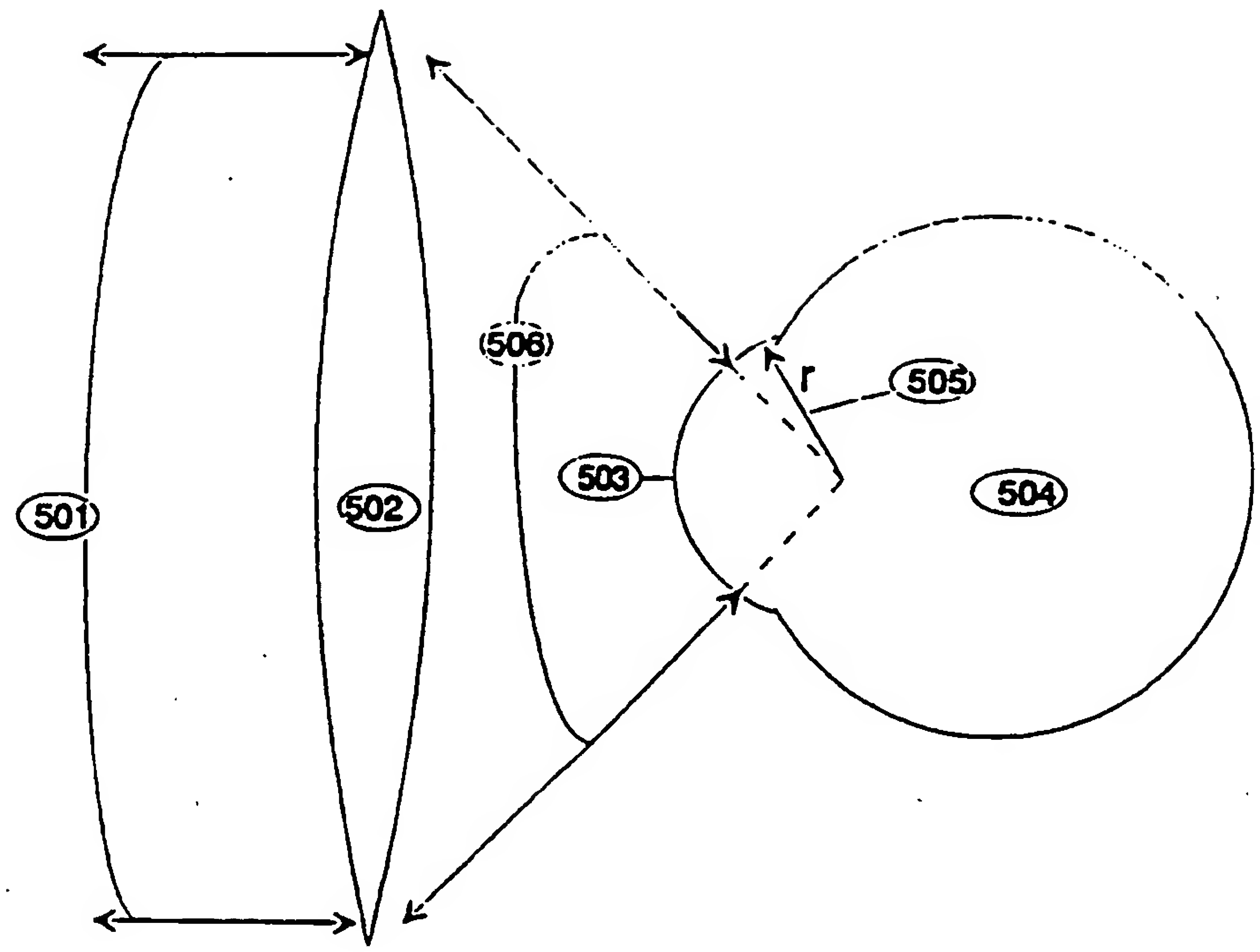


Figure 5

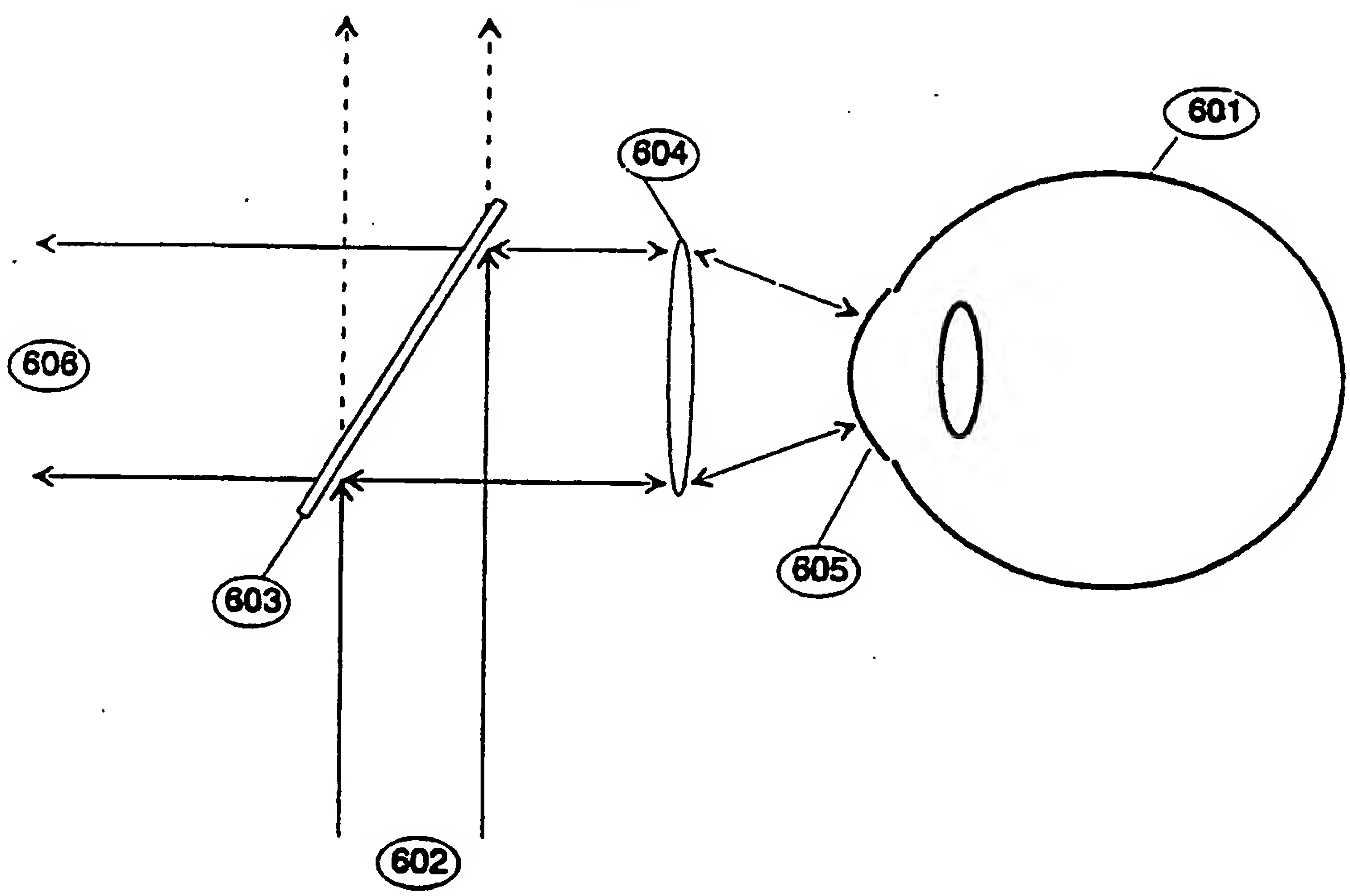


Figure 6

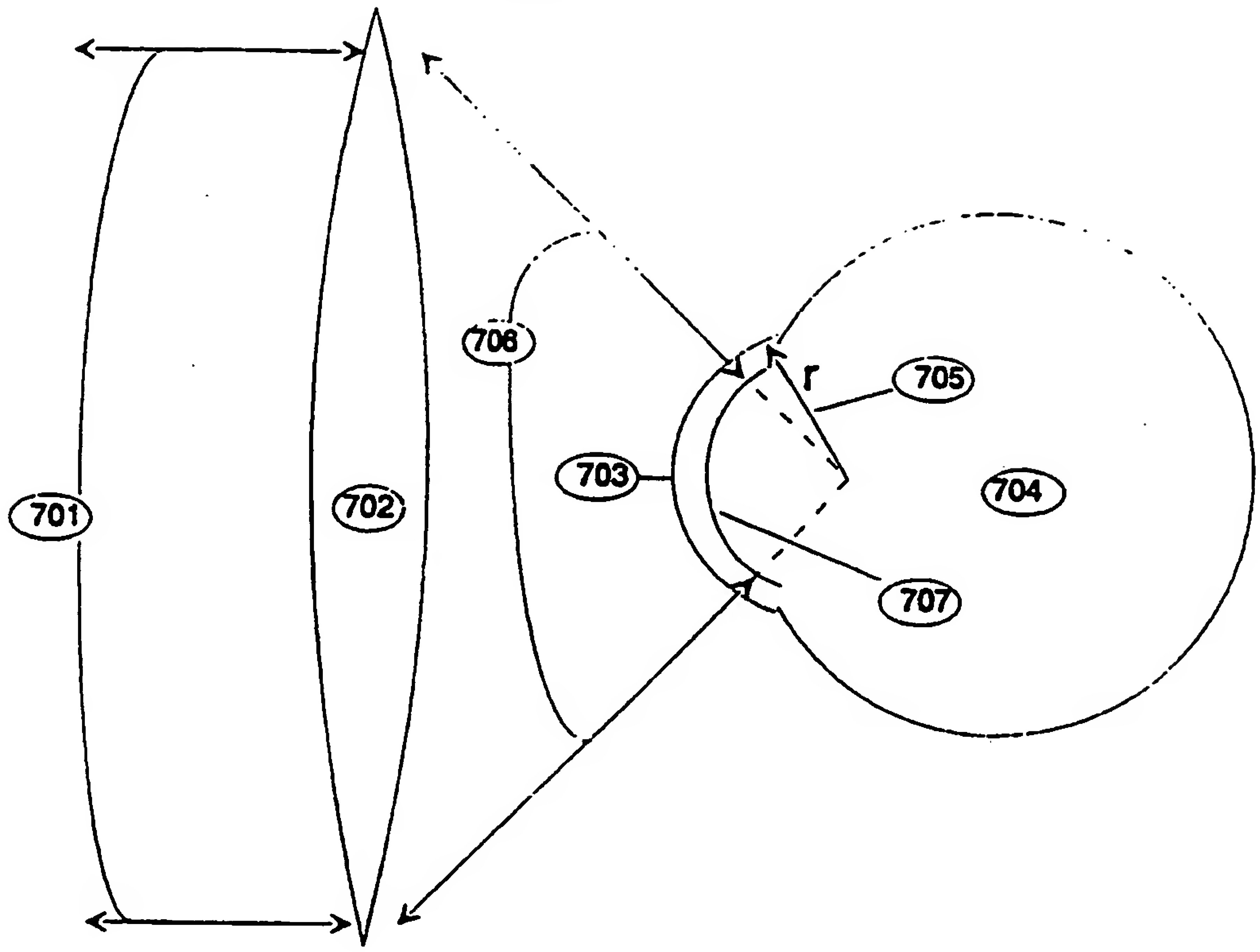


Figure 7

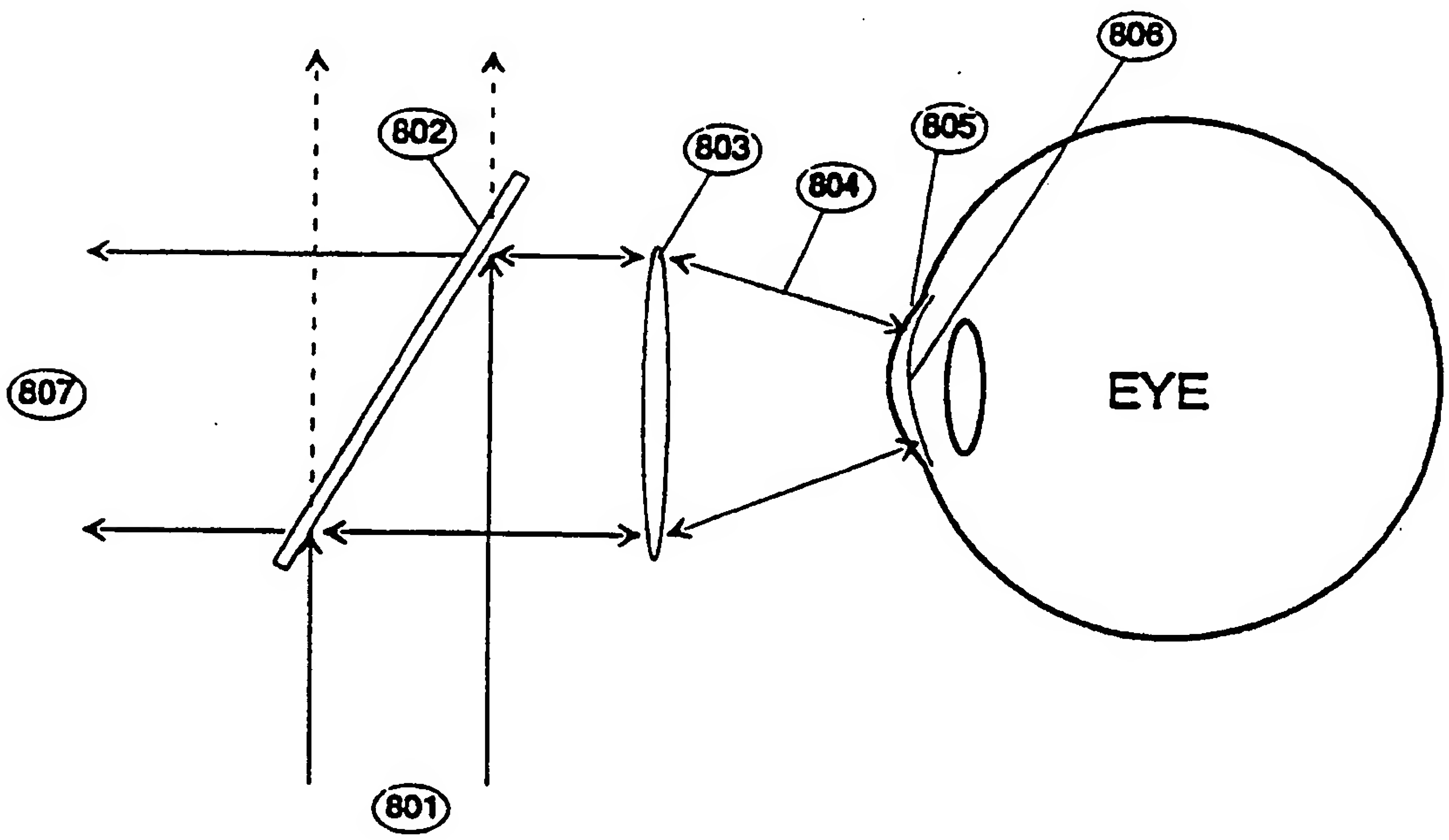
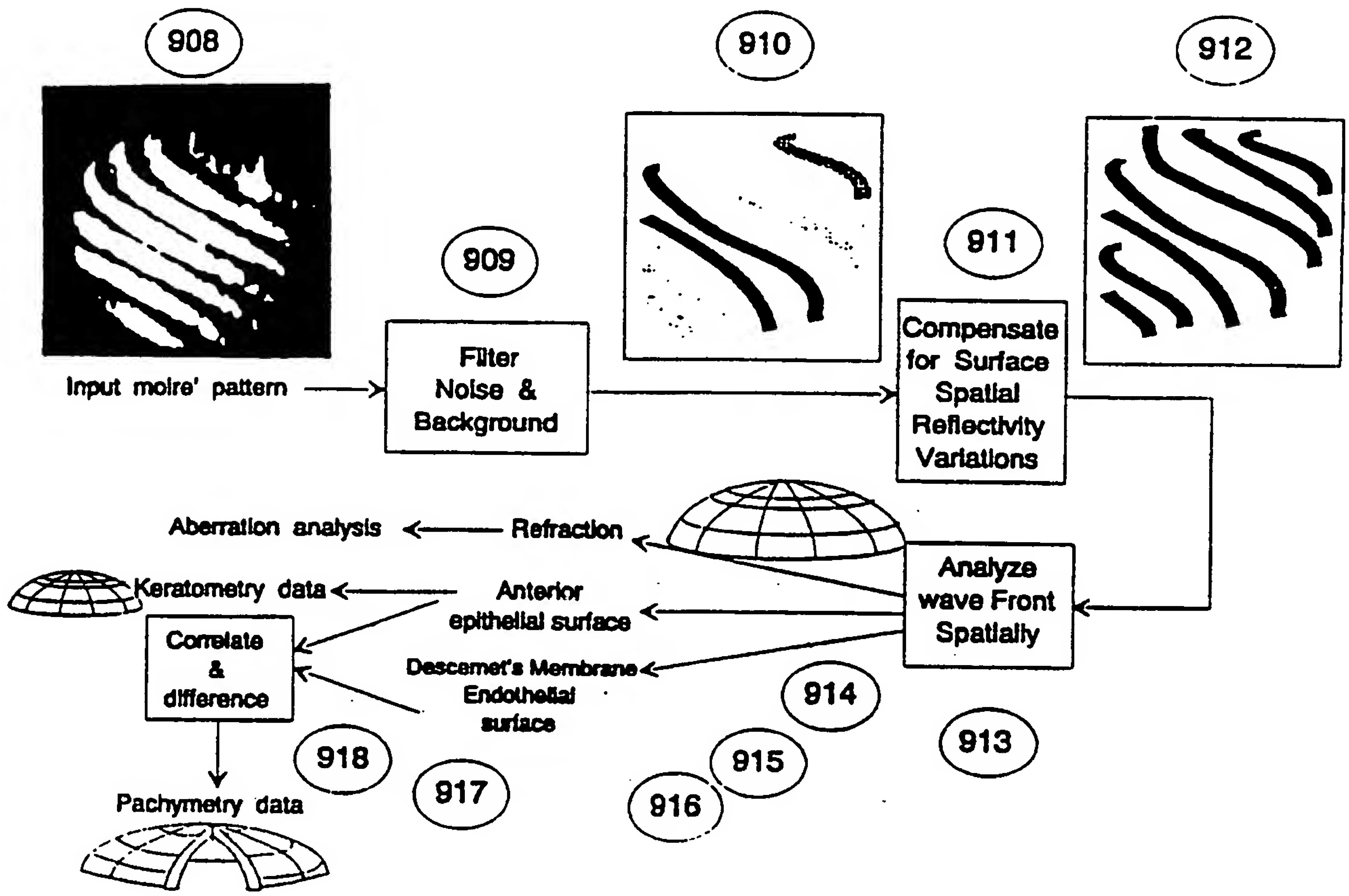


Figure 8


908
910
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911
Input moire' pattern
Filter Noise & Background
Compensate for Surface Spatial Reflectivity Variations
Aberration analysis
Refraction
Keratometry data
Anterior epithelial surface
Analyze wave Front Spatially
Correlate & difference
Descemet's Membrane Endothelial surface
914
913
918
917
915
916
Pachymetry data

Figure 9

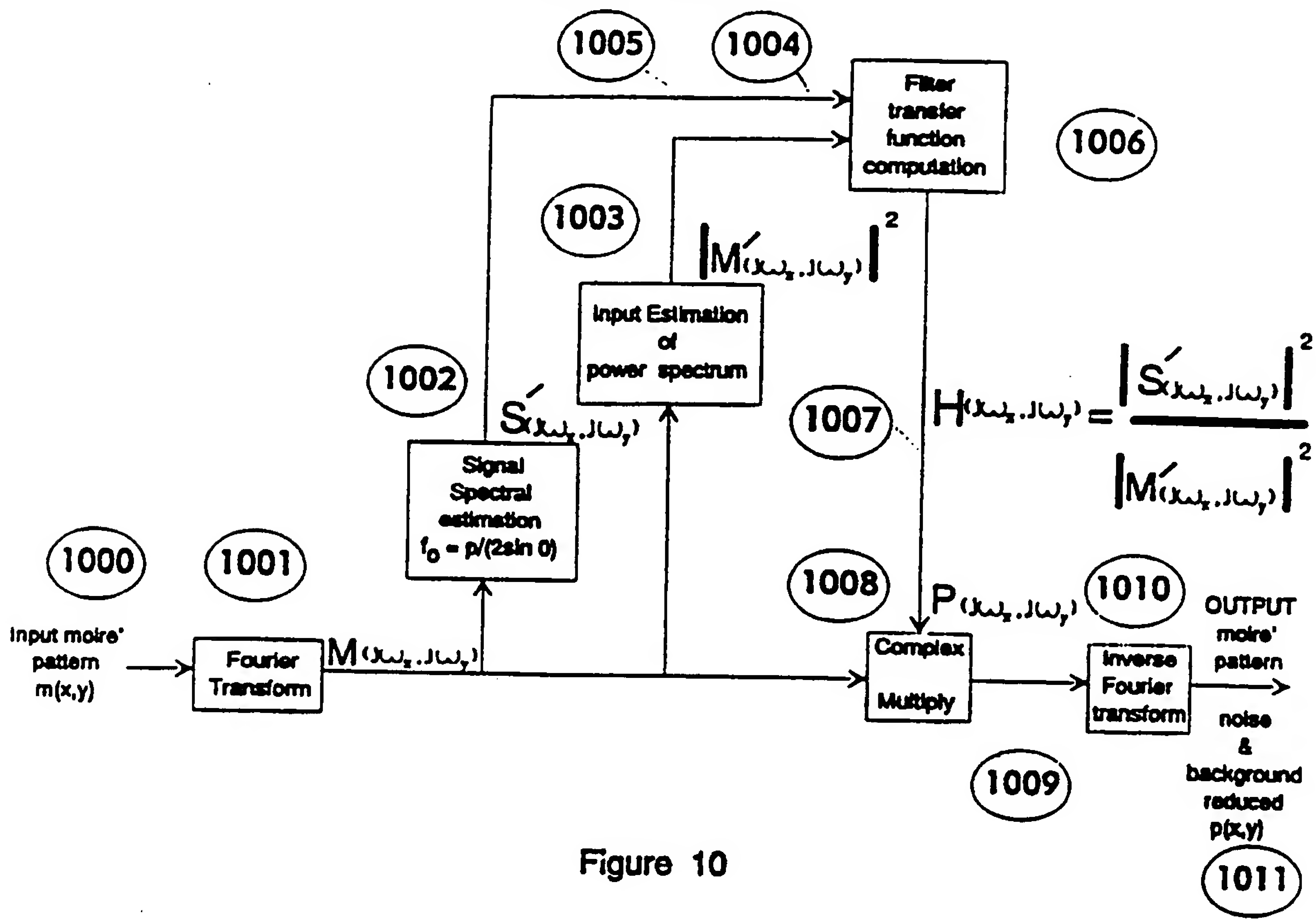

Figure 10

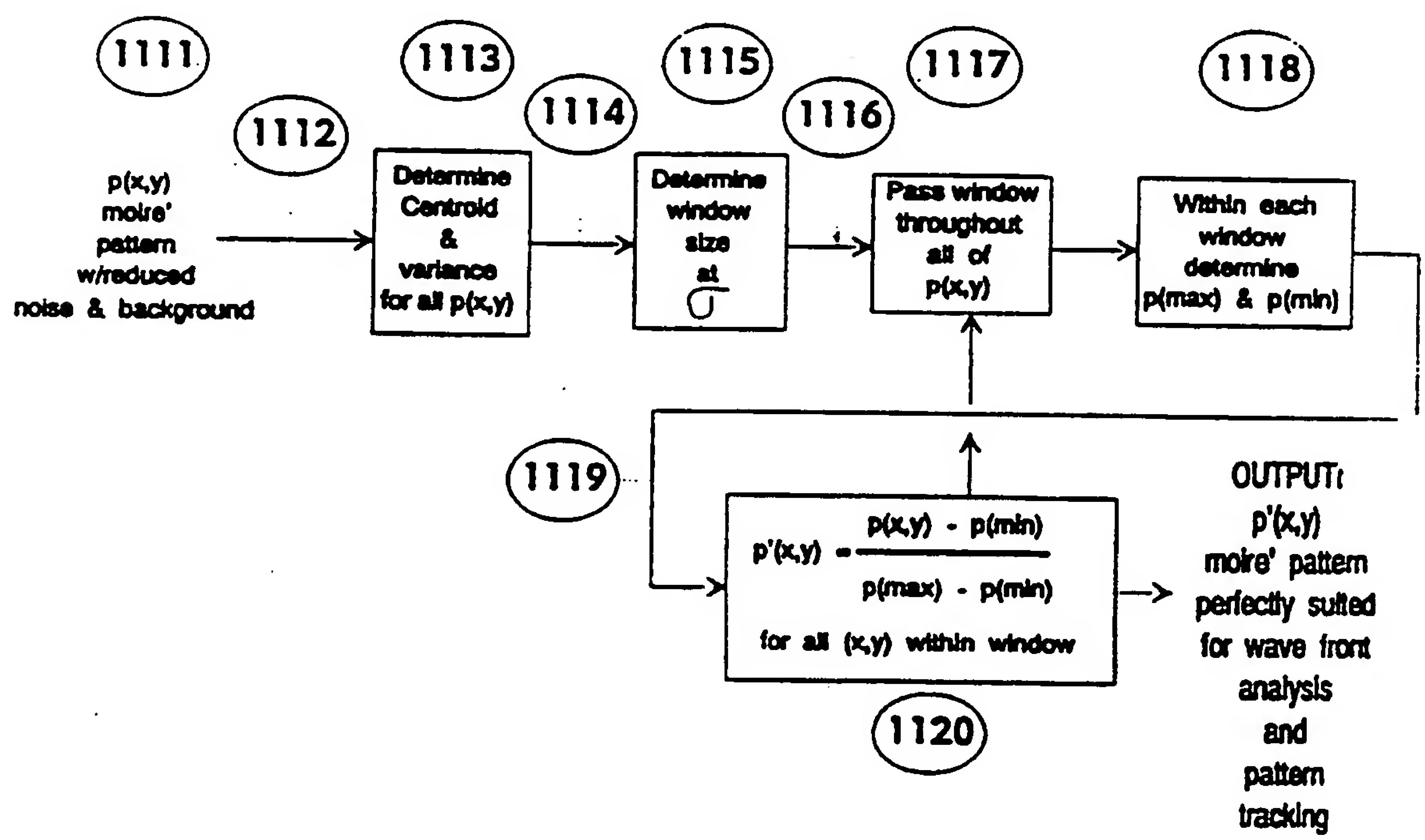

Figure 11

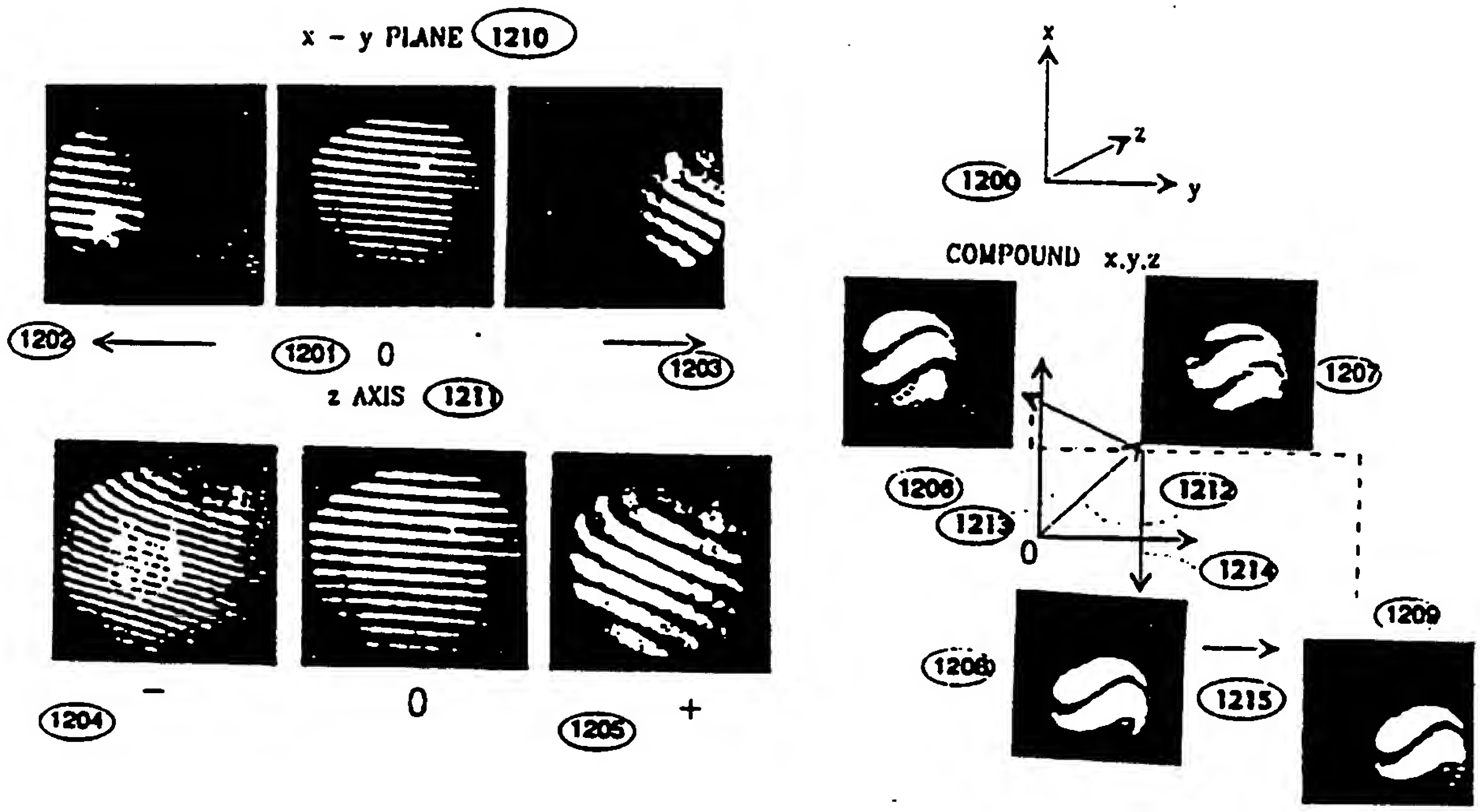
x - y PLANE 1210
1202
1201 0
1203
z AXIS 1211
1204 -
0
1205 +
x
z
1200
y
COMPOUND x,y,z
1207
1206
1212
1213
0
1214
1209
1208
1215

Figure 12

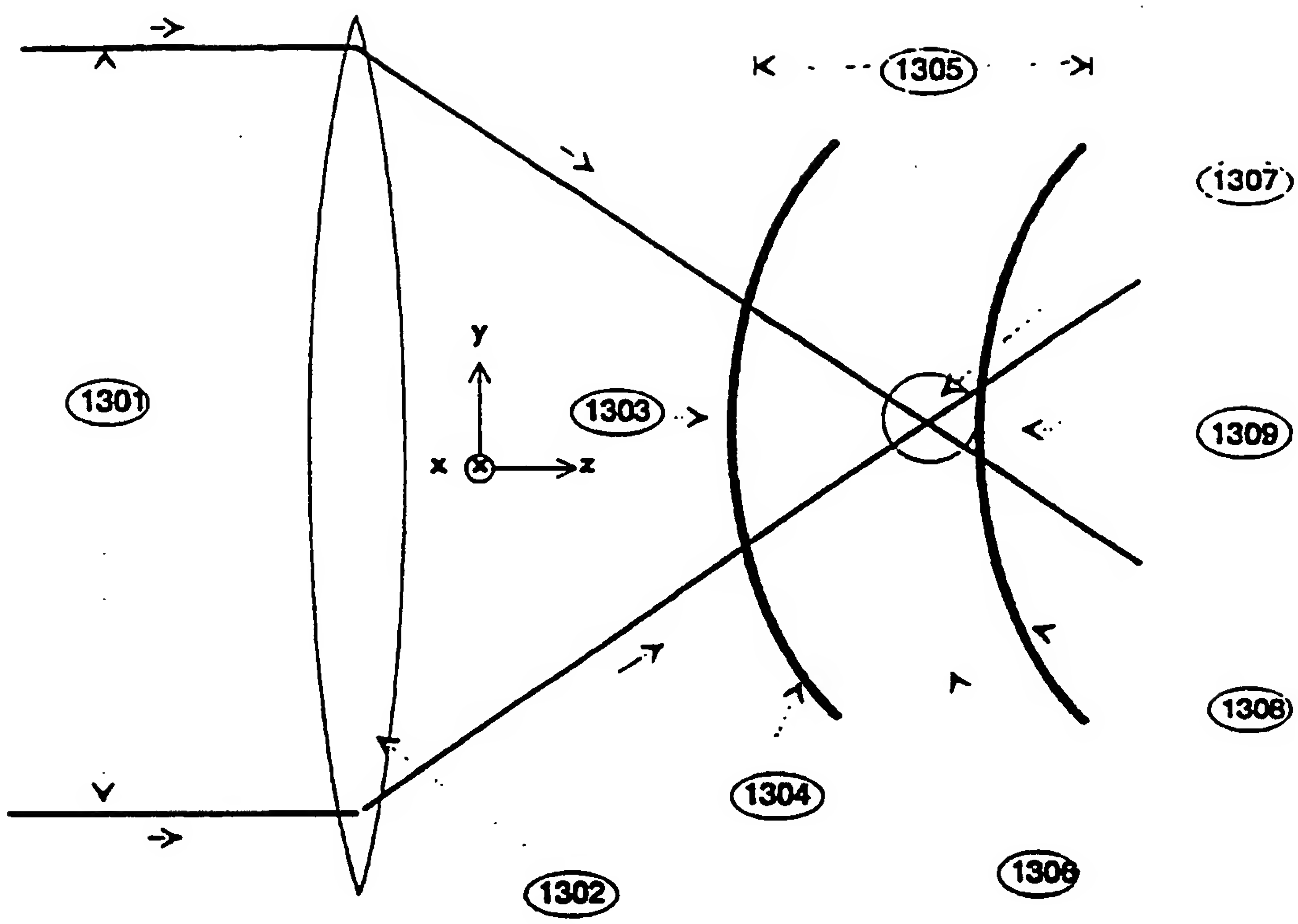

Figure 13

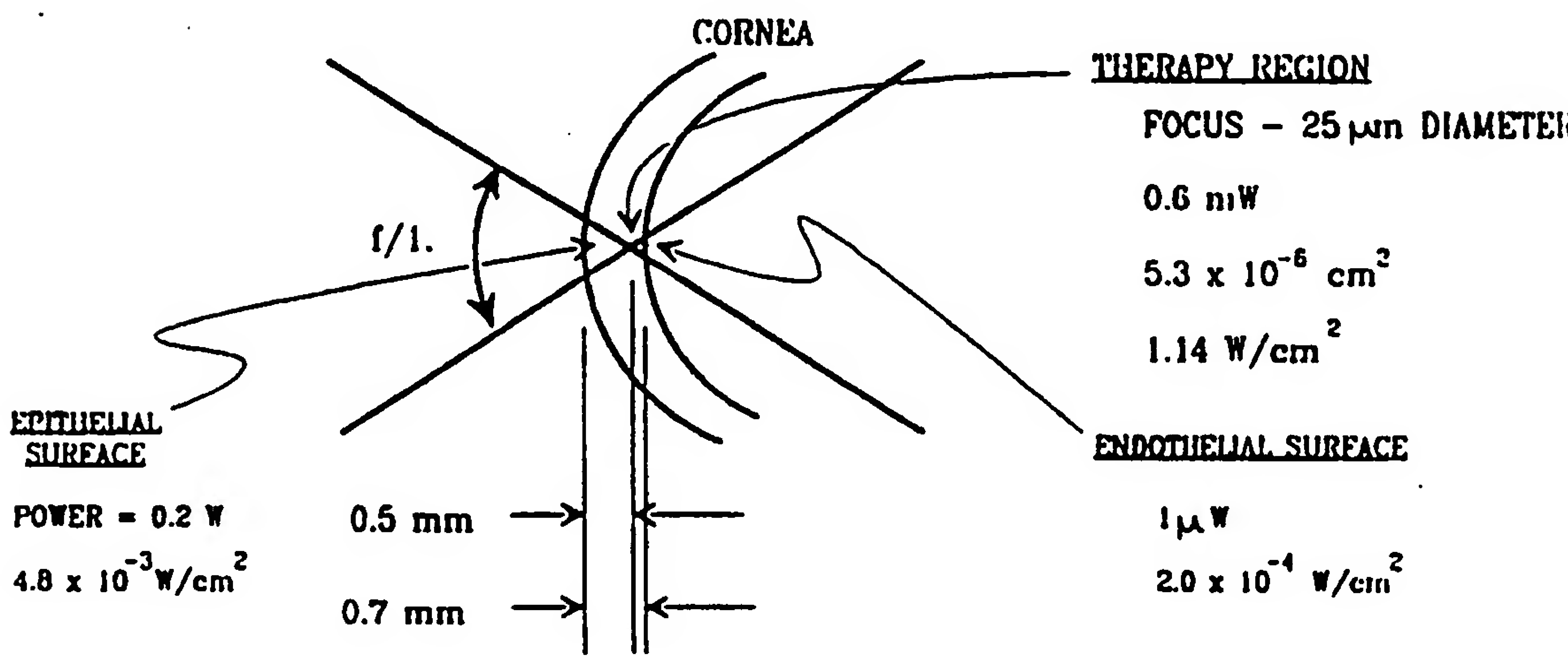

Figure 14

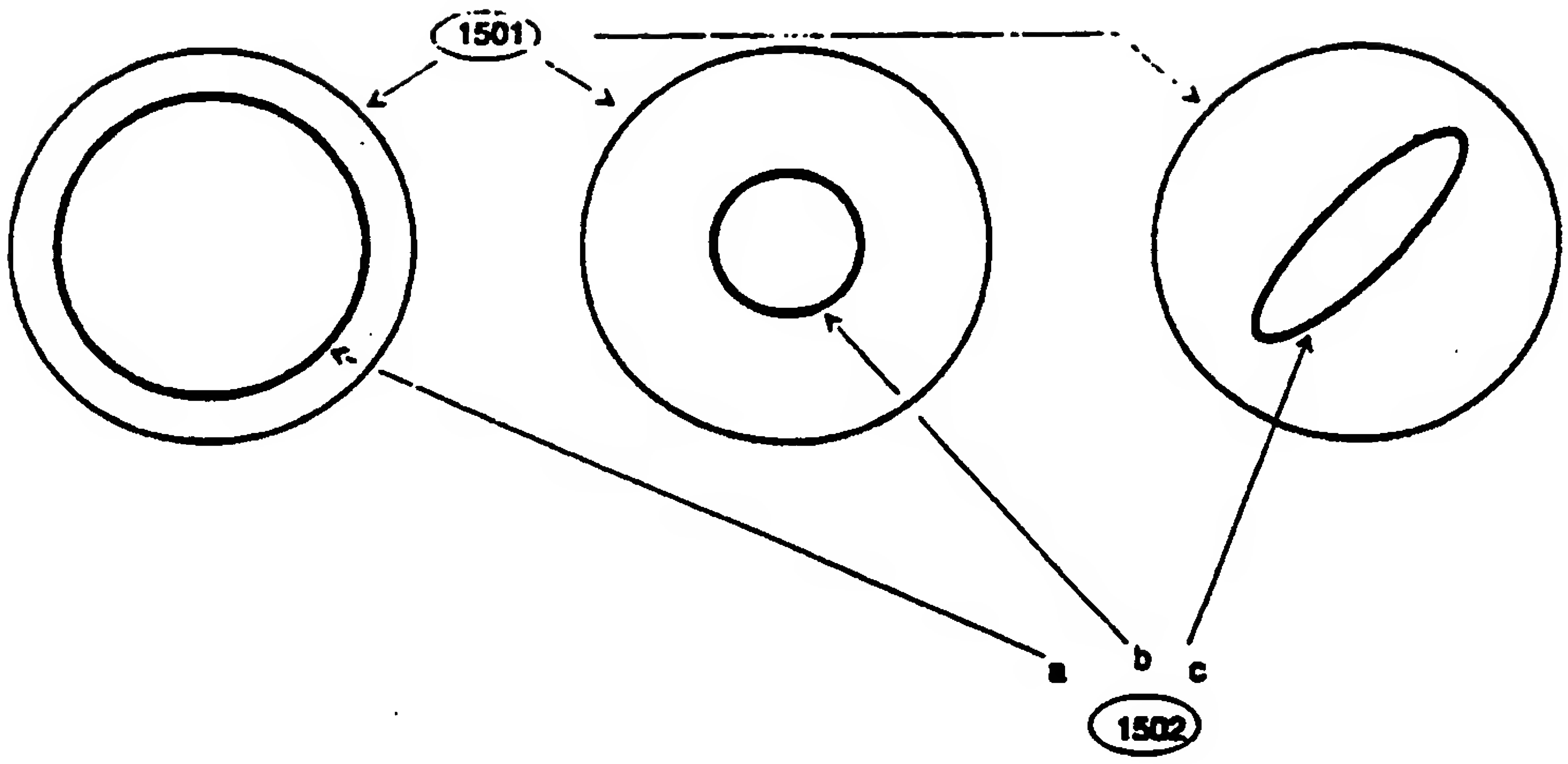

FIGURE 15

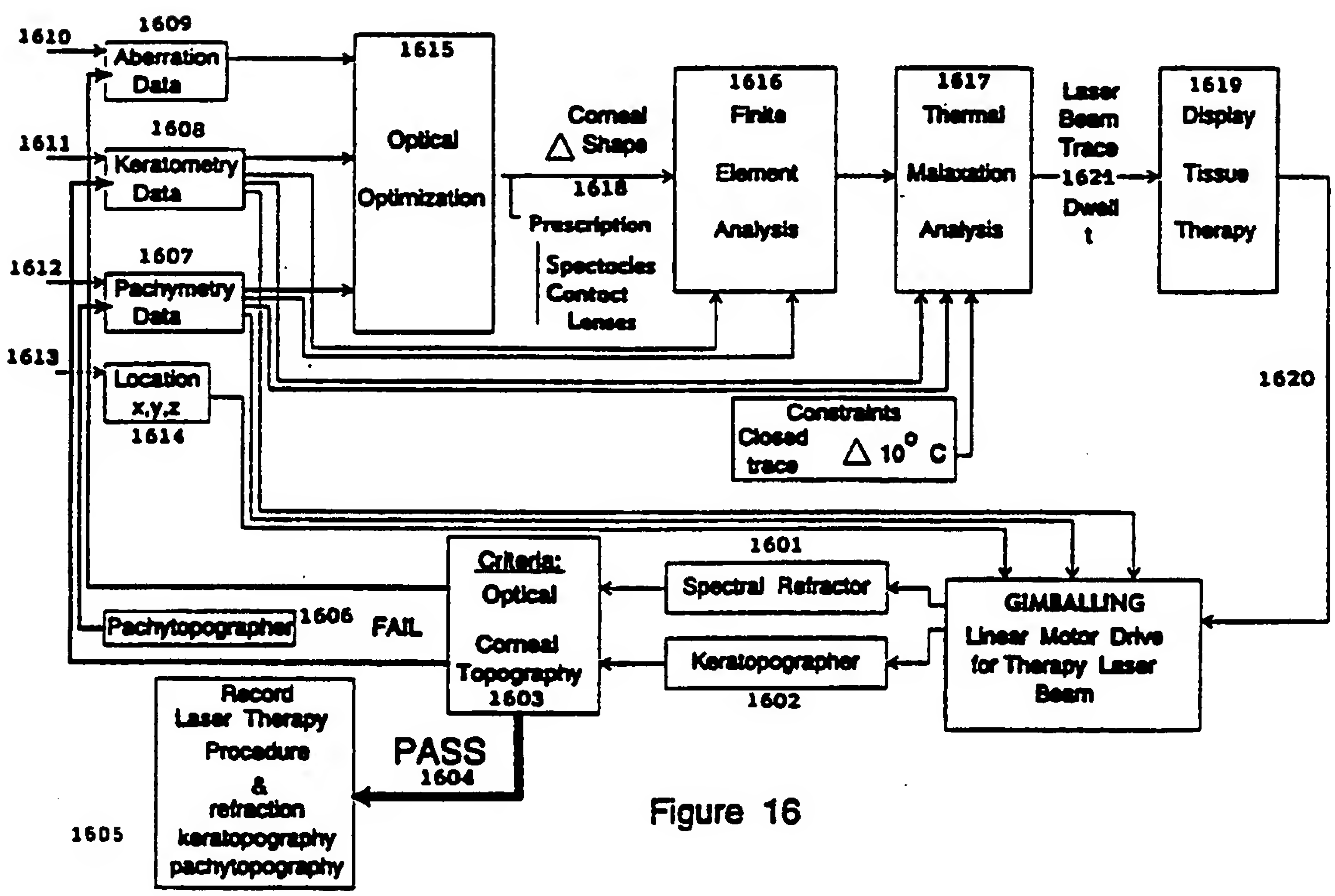

Figure 16

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US91/04976

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC
IPC(5): A61B 3/10
U.S. CL.: 351/212,221

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
U.S.	351/212,205,221 128/395

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	US,A, 4,692,003 (ADACHI et al.) 08 SEPTEMBER 1987 See entire document	1-30,84-86
X	US,A, 4,721,379 (L'ESPERANCE) 26 JANUARY 1988 See especially cols. 5-7	57-83,89
A	US,A, 4,964,715 (RICHARDS) 23 OCTOBER 1990 See cols. 2,3	57-83,89
A	US,A, 4,984,883 (WINOCUR) 15 JANUARY 1991 See cols. 3-5	1-30,84-86

* Special categories of cited documents: [10]
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search
22 NOVEMBER 1991

Date of Mailing of this International Search Report
04 DEC 1991

International Searching Authority
ISA/US

Signature of Authorized Officer
PAUL M. DZIERZYNSKI